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Final Report

DEVELOPMENT OF A SUBSURFACE DRILL SYSTEM FOR POST-APOLLO MISSIONS

March 1967

Contract No. NAS 8-20547

Submitted to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama

by

WESTINGHOUSE DEFENSE AND SPACE CENTER
Aerospace Division
Baltimore, Maryland

ABSTRACT

The feasibility of providing coolant to the drill bit, of chip removal and of dry diamond rotary drilling was demonstrated.

Based upon the feasibility demonstrations, continued development and an established technique of core retrieval without drill string removal, a lunar drill engineering model was designed to have the capability of drilling in dry rock to a minimum depth of 100 feet when operated by a space suited astronaut. The drill system and component development are discussed. Two drill systems of this design were fabricated and delivered.

Limited laboratory system testing on basalt rock has shown that the system is a workable tool, although further development will be necessary. Recommendations for future development approaches are provided.

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TABLE OF CONTENTS

Page

Page

LIST OF ILLUSTRATIONS

SUMMARY

Prior to the actual design of the engineering model, the objective was to demonstrate the feasibility of providing coolant to the bit of the manner of chip removal and of dry diamond rotary drilling. These feasibility objectives were demonstrated.

The objective for the engineering model design was to develop a suitable facsimile of a lunar drill prototype capable of cutting core samples in dry rock to a depth of at least 100 feet, and to be able to operate in a high vacuum. The restraints were:

- Total drill system package limited to 200 pounds excluding power supply
- Weight of vehicle or shelter, which might be applied to drill operations, could be approximately 5000 pounds
- Any gases, liquids, or solids used in drilling operation must be considered part of the drill system weight
- Power would be limited to a maximum of 5 kW
- Hole cave-in was to be prevented for the first 5 feet
- Drill system to be operable by a space-suited astronaut.

Two engineering models were delivered - one in a disassembled condition for component testing by MSFC, NASA. The assembled model was used to demonstrate the workability of the system for drilling in dry basalt rock and to recover cores.

Whereas the engineering model drill system did not achieve all of the objectives of the program, significant advances were made toward the goal of developing a reliable tool for the post-Apollo missions.

- Diamond rotary drill bit technology was advanced to the point where over 10 feet of basalt can be drilled with an internally cooled bit, and to where there is evidence that the internal coolant may not be necessary. These advances were demonstrated by one or more tests.

- Automatic control of the drilling factors, once the settings are made, and an alternate manual control capability.
- Automatic protection circuitry to shutdown the drill system where the automatic control settings are exceeded and for operator safety. Indicators are provided to indicate the shutdown cause.
- Systems to provide rapid recovery of cores and to remove drilling chips.
- A bit cooling system including a rotary joint which, under vacuum conditions, changes the coolant flow from a straight to a rotary path.
- A multihorsepower dc motor, which will operate under high vacuum conditions.
- A solid lubricated gearbox, which gives promise of operation in a high-vacuum environment as the result of tests on solid lubricated gears and bearings
- A method of casing the hole for the first 5 feet to prevent cave in.
- A drill system which is designed to be assembled and operated by an astronaut under lunar conditions.

The weight objective was not achieved. The use of new engineering materials, the potential results of the recommended engineering studies, and the potential elimination of some components give promise of meeting the weight restraint.

The critical hardware components were delivered later in tne program than scheduled and could not be thoroughly tested prior to the drill system tests. The system testing was reduced in scope due to the delay in component delivery, component failures, long replacement sidelobes, and funding problems. The workability of the drill system design was demonstrated to NASA personnel prior to delivery by dry drilling into basalt and by breaking the core.

The limited laboratory system testing has indicated that further development will be required in the following areas:

- Diamond Bit Design
- Chip Removal
- Gear Box
- Drill String Coupling
- Drill Motor

- **Automation Techniques.**

The recommended approaches are discussed in Section 3.

The drill system test gave indications that it may be possible to drill without internally cooling the bit. Confirmation of these indications would permit the elimination of the weight and the failure potential of the bit coolant structures which include the heat exchanger, rotary joint, valve assembly, and the complex drill string joints. With the elimination of these components, the number of drilling operations could be reduced, other operations be simplified, and the system made more adaptable to automation techniques.

1. INTRODUCTION

1.1 PROGRAM OBJECTIVES

The overall objective of the Lunar Drill Program was to develop a lunar drill capable of taking lunar surface cores to depths of at least 100 feet and to examine methods and techniques of extending this concept beyond 100 feet.

The specific objectives of contract number NAS 8-20547 were to demonstrate feasibility of the Westinghouse concept by performing laboratory feasibility tests on specific high-priority elements during the first 120 days of the contract and to develop an engineering model which was a suitable facsimile of a lunar drill prototype capable of taking core samples in dry rock to a depth of 100 feet. The work was to be accomplished within the following restraints:

a. The total weight of the drill including any coolant material, but excluding the power supply, should not be greater than 200 pounds.

b. The weight of the vehicle or shelter which might be applied to the drill during drilling operations was approximately 5,000 pounds mass. Because of mounting restrictions on the vehicle and the reduced lunar gravity, the practical limitation for thrust was approximately 400-pound force.

c. The maximum power level for the drill should not exceed 5 kW.

The deliverable items on the contract were to be:

a. A set of engineering, shop, and assembly drawings of the engineering model of the drill.

b. An engineering model of the drill.

c. One unassembled engineering model with five lengths of rigid coupling.

d. Monthly, quarterly, and final reports.

1.2 CONCEPT AND PHILOSOPHY

The Westinghouse lunar drill concept is predicated on the design and development of an adaptation of an operational system, the E. J. Longyear Wireline Drill. The wireline drill has been in widespread use for 17 years.

Figure 1-1 shows the engineering model and figure 1-2 shows the mockup which depicts the major components. The wireline drill system, like conventional drills, consists of a drill-rig, a prime mover, drill rods, a core barrel and a bit, and employs conventional rotary drilling. The unique element, which sets the wireline drill system apart from other drilling systems and techniques, is the method of core recovery. As the core is cut, it is collected in a retractable core barrel which can be lifted to the surface without withdrawing and dismantling the drill rods and leaves the bit in place. After a length of core is withdrawn, the same or an alternate retractable core barrel can be lowered into place inside the drill rod and drilling continued. This technique permits a large reduction in the operation time of the drill compared to other drilling systems and is a very desirable feature considering the high man-hour cost on the moon and the short staytimes scheduled.

The comparatively few and simple operational steps necessary to obtain a core should result in a highly reliable drilling operation. This has been demonstrated over the period of years on earth and highly desirable for lunar drilling operations when a man is hampered by a space suit environment. A special casing is drilled in for the first 5 feet to collar the hole to prevent surface and immediate subsurface cave-in. The drill string itself serves as the casing for the hole below the top-of-the hole casing.

This system has been adapted to operate in the lunar environment by providing a sealed dc motor for vacuum operation, and solid metallic base lubricants for bearings and gears. The use of lightweight construction is a continuation of the weight modification program that has already resulted in

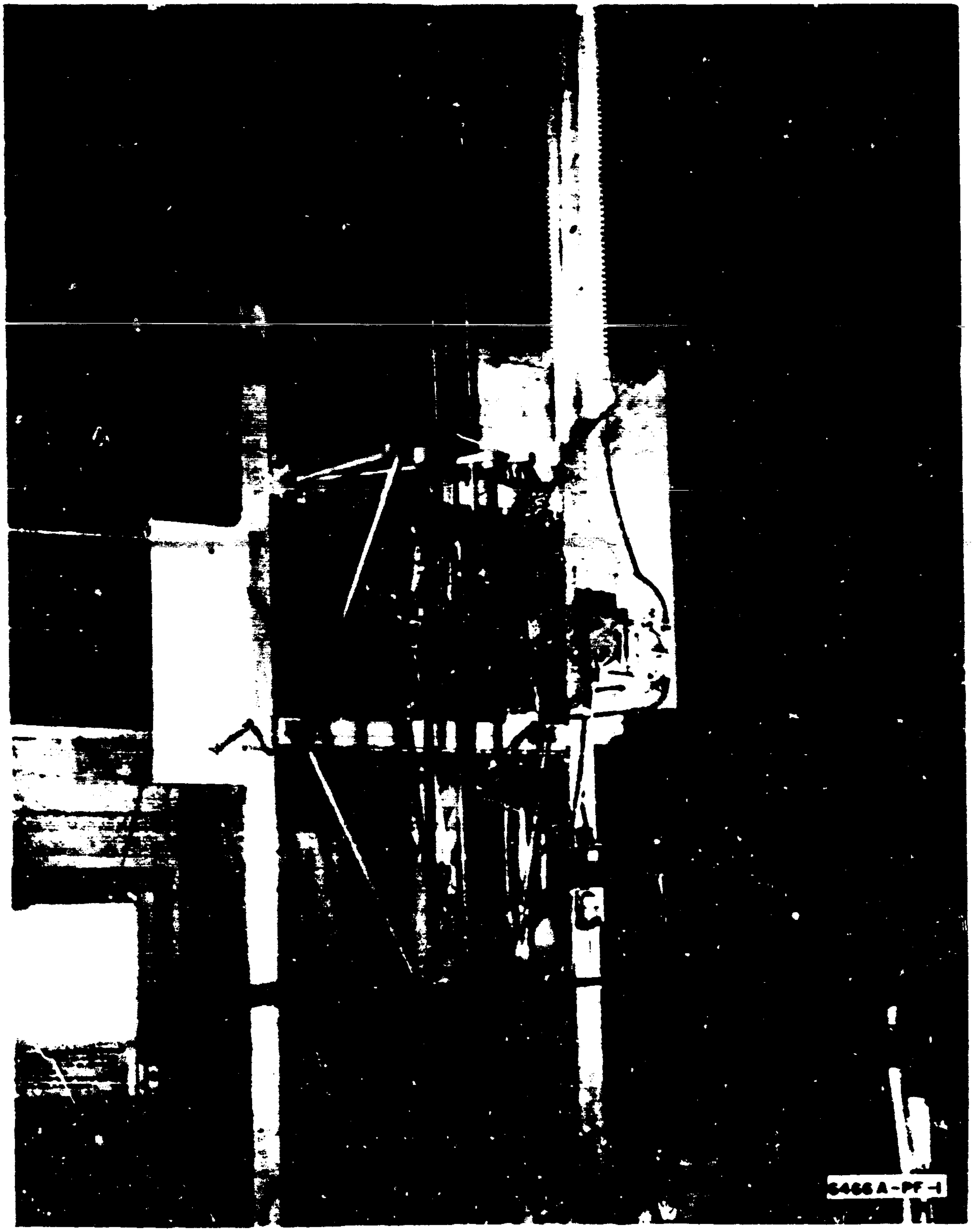

Figure 1-1. Lunar Drill Engineering Model

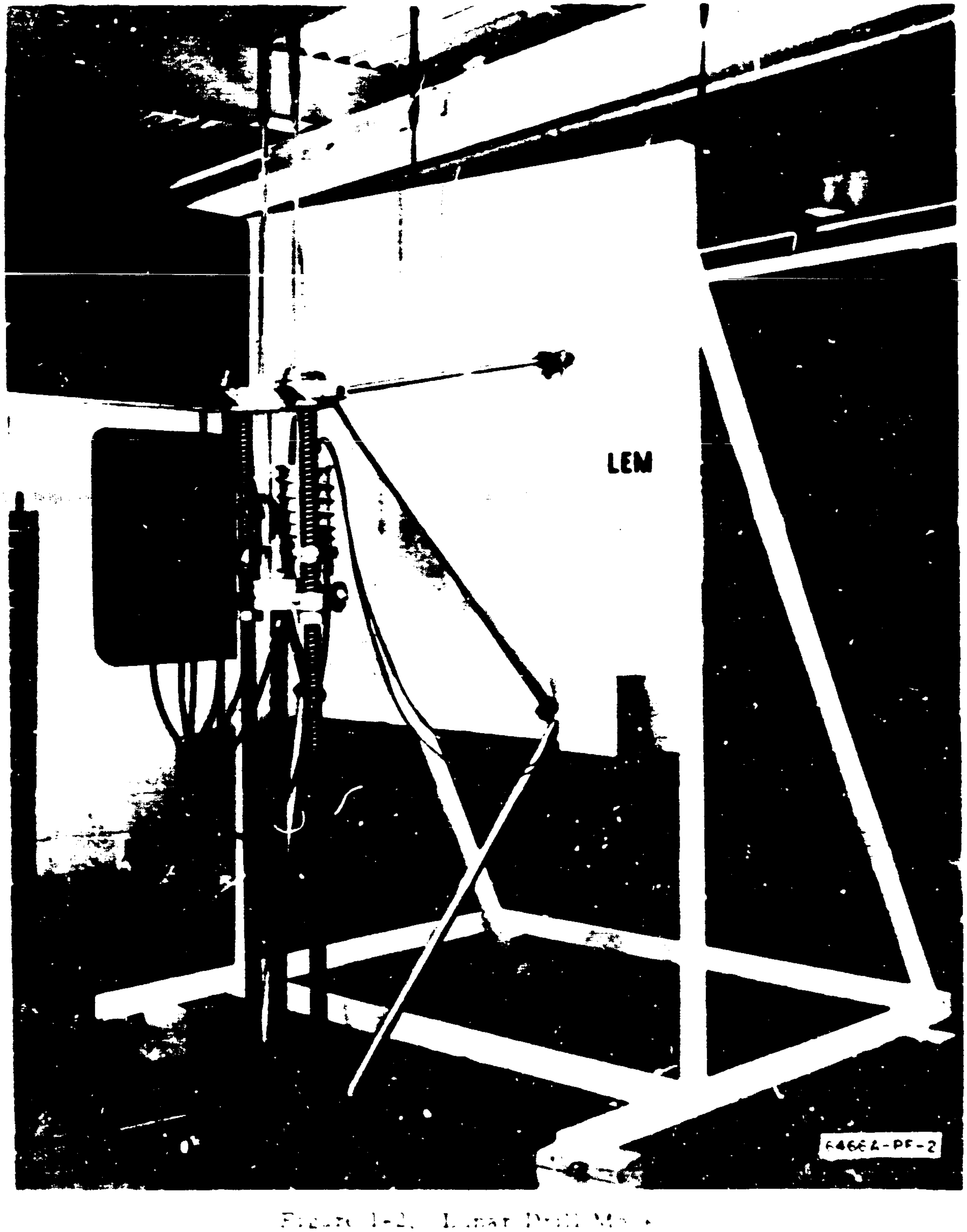

Figure 1-2. Lunar Drill M[illegible]

the development by the E. J. Longyear Company of a helicopter transportable drill unit for use in remote areas of the U.S.A., Canada, and India.

A preliminary analysis shows that a 100-foot hole will take approximately 40 hours to install, drill, and collect samples in dry rock using the wireline techniques.

No problems of a nature which would make a lunar drill unfeasible have come to light during the Westinghouse studies of the lunar drilling problem. The major engineering problems, to which the development program was addressed were bit design, chip removal, bit temperature control and heat removal in the absence of naturally available cooling fluids such as would be encountered in the lunar environment.

In the design of the Westinghouse drill, the limitations of the space-suited astronaut was one of the major tradeoff areas considered. As demonstrated by the problems encountered by the Gemini astronauts during extra-vehicular activity, it is evident that a maximum degree of automation should be provided to lighten the astronaut workload. However, according to the NASA specification, the overall drill system weight was to be limited to 200 pounds. Thus, a compromise was struck between automation and the resultant lightening of the astronaut workload on one hand and weight saving on the other. Westinghouse believed that it was more important during this development to demonstrate the feasibility of the overall approach than to design maximum automation into the equipment at the expense of time, weight, and additional funds. Thus, automatic control and protection devices have been made a part of the system, but full automation could not be incorporated.

Due to the limited time and funds available for the development of the engineering model and the many areas in which significant research and development were necessary, it was not possible to carry out an extensive component and subsystem development testing program. The results of previous programs in such areas as drilling, solid lubricants, and sealed motors for vacuum application were drawn upon heavily as background for the engineering model. Background obtained from these programs and experiences indicated a high probability of success in these development areas.

The one area in which little or no previous experience was available was that of dry (no coolant or lubricant external to the bit) diamond drilling. As a result, this subject received considerable attention. To date, it has been demonstrated that a dry diamond bit can drill to depths in excess of 10 feet in a dry rock. As will be discussed in some detail later in this report, there are a number of improvements which can be made to the present bit design which should greatly increase its life.

From the overall systems viewpoint, the decision, not to enter into an extensive research program but to extrapolate the results of other programs to the particular problems to be encountered in the lunar drill, resulted in subsystem and component failure during the systems test. Some failures were related to quality control problems rather than the design. The failures, the resulting engineering changes, and the difficulties with funding caused the completion of the program to be extended beyond the expected contract end date of July 29, 1966.

1.3 PROGRAM EVOLUTION

Westinghouse was required to demonstrate the feasibility of certain priority requirements during the first 120 days of the contract. Specifically, these priority requirements were:

a. To demonstrate the mechanical arrangement to provide coolant to the bit.

b. To demonstrate the manner of chip removal.

c. To demonstrate feasibility of the rotary dry diamond bit drilling.

These feasibility demonstrations were completed as of 10 December 1965. On 13 January 1966, conditional approval for the continuation of the contract work was received from the contracting officer. As a part of this approval, it was stated that "... with much research and development (the rotary concept) is a possible tool for lunar subsurface drilling. More realistic tests of the bit operation and life time should be carried out during the continuing development work."

Westinghouse fully appreciated the necessity for additional research and development and complied with the spirit of the contracting officer's recommendation within the limitations of time and funds imposed by the contract. Upon completion of the feasibility tests and receipt of the contracting officer's approval to continue work, firm arrangements were made within Westinghouse and with the subcontractor, E. J. Longyear Company, to develop the necessary hardware for the lunar drill system. Delivery of sufficient numbers of subsystems to assemble the system and start systems testing was accomplished during July. In the period from July to 2 December 1966, iterative testing, modification, and upgrading of the system were undertaken and drill system operation was demonstrated successfully.

1.4 SYSTEM DESCRIPTION

Figure 1-1 shows the assembled engineering model of the lunar drill mounted in the laboratory. It will be mounted in a similar fashion to an AES payload such as the lunar module.

The drill frame, sealed motor, gearbox, ball screws, and chuck form an assembly which folds for transport. Aluminum was used wherever possible for weight reduction. The sealed motor has a closed loop cooling system consisting of hoses, external pump, and a heat exchanger. For long term field testing, an air-cooled motor is supplied and appears in the illustration.

The gearbox has a neutral position and two rotational speeds for driving the drill string. In addition, it supplies power for a hoist and for vertical movement of the drill carriage. Two back-to-back hysteresis clutches control these hoist and feed movements when suitably energized by the controls and with the hoist or feed gear arrangement set in the appropriate position.

The drill string is connected by a chuck to the bull gear. The 100-foot drill string consists of 5-foot lengths of drill rods and auger-flighted core barrels and a bit. When the core barrels only are used for the first 10 feet of drilling, a core barrel-chuck adapter is employed. The auger flights on the core barrels are designed to lift the drilling chips to a maximum height of 15 feet where they are moved inside of the core barrel assembly.

The bit has an internal manifold which permits coolant to remove heat from the bit crown. The bit crown contains diamonds laid out in a snow plow design which moves the chips to the outer diameter where they enter the auger flight system. The diamonds are oriented so that the hard vectors are positioned in the direction of cutting to reduce diamond wear.

The bit coolant system is a closed loop consisting of a radiator, a valving system for preventing coolant loss during drill string additions, hoses, a rotary joint for transferring coolant to and from the rotating drill string, passages in the chuck, adapter, drill rods, core barrels and bit. Special seals and couplings are provided to prevent coolant loss.

Bit temperature is sensed by a thermistor embedded in the bit matrix. The power to and the signal from the thermistor is passed by signal leads through contacts at every drill string joint to the rotary joint. An appropriate signal bridge and rotary transformer passes the signal to the control indicator via the signal conditioner circuit.

The core recovery system is built around the wireline technique which eliminates the requirement for removing the drill string to recover the core. An inner core barrel - chip basket assembly is positioned internal to the outer core barrel assembly. As the drill string advances, the inner core barrel assembly slides down over the core and the chip basket receives the chips from the auger flight system on the exterior of the outer core barrel. When the 5-foot core is produced, the drill string is raised 1 to 2 inches. A core lifter, based on the chinese finger principle, quickly grabs the core, and the upward pull of the drill string breaks the core. The hoist is employed to drop the overshot, a mechanism which locks to the inner core barrel assembly, down the drill string annulus. The hoist pulls the inner core barrel to the surface where the chips and core can be removed.

The control and protection unit receives bit temperature, thrust, feed rate, axial limit, gear position, and support structure vibration signals to maintain automatic control of the drilling operation and to provide protection against damage. Visual fault and operating condition indications are provided by indicator lamps. Manual control is also provided. A remote control, when energized, can control the drill up to 100 feet from the drill site.

A motor starter is provided to limit motor power input to the gearbox, and a signal conditioner is utilized to convert the sensor signals to an appropriate form for control operation.

The sealed motor requires a filtered 100 V dc power supply and a 115 V ac 60 Hz power supply for the external pump. The air-cooled motor requires a 28 V dc power supply.

The controls require a filtered 28 V dc power supply.

The major components and total weights of the engineering model are listed in table 2-3.

2. TECHNICAL DISCUSSION

2.1 DRILL BIT DESIGN AND CUTTING REMOVAL

2.1.1 General Background

Bits designed for earth use are normally of the following types:

- Carbide bit
- Roller bit
- Diamond bit

Carbide bits are used for rotary, percussion, and rotary percussion drilling of rocks. Because it has a high compressive strength, carbide bits find wide use in percussion-type drilling.

Although carbide has a compressive strength of the same order of magnitude as diamond, it does not compare favorably with diamond for hardness. As a result, diamond drills are preferred for rotary drilling in igneous rock.

Rolling cutter rock bits have cutters, roughly conical in shape, assembled on bearings attached to the bit body. With a thrust load on the bit, the cutters break up the rock into chips as they are forced to roll on the bottom of the hole when the drill stem is rotated.

Several varieties of roller bits which can successfully drill a variety of rock types are commercially available. However, the roller bit is not considered for use in the lunar drill system for the following reasons:

- Heavy thrust levels are required.
- The hole to core size efficiency is poor.
- Core recovery in hard, broken rock, or rubble is poor.

The diamond bit is generally cylindrical in shape and set with diamonds in the area that cuts the bottom of the hole and gage. In commercial bit patterns of diamond setting, diamond size and number, head shape, and water courses are determined by the kind of formation to be drilled. Generally, larger and fewer diamonds are used in bits drilling in soft formations and smaller and greater numbers of diamonds are used in hard formations. Since soft formations tend to build up on the bit matrix, larger diamonds are used on the soft formations.

Diamond bits provide the capability to drill through any known earth material and are also expected to be capable of drilling through the lunar material. The design of a diamond bit best suited to the lunar formations and environment will be vitally important to the success of core drilling mission. Some of the aspects of diamond bit design that will require attention are covered in subsequent paragraphs.

a. Diamond Loading

As the bit rotates, the diamond velocity and penetration rate per inch of travel varies as the distance of the diamond from the center line or axis of rotation. Each diamond should have definite penetration rates and each diamond should be stress-analyzed so that it would be at a safe working level. Safe load limits for diamonds have been determined with respect to size, shape and grade.

b. Matrix Material

The hard sintered metal that holds the diamond in the bit is called a matrix. Most North American manufacturers of surface set diamond bits now use a matrix of sintered powdered metal. The matrix hardness classification has three general divisions: standard (about 30 Rockwell C), hard (about 40 Rockwell C), and extra hard (about 50-60 Rockwell C). Careful consideration of the formation to be drilled determines the hardness of the matrix to be used.

c. Friction of a Diamond

The coefficient of friction for the diamond decreases as a function of load. Thus, by proper thrust loading of the bit, the coefficient of friction can be reduced appreciably. In the earth environment, for example, proper loading reduces the friction coefficient as much as threefold. At the same time, inadequate loading of the diamonds reduces the life and performance of the bit by what drillers refer to as "polishing or burnishing the bit."

Another method of substantially reducing the coefficient of friction is to introduce a gas or atmosphere that will contaminate the surfaces of the diamond by forming a friction-reducing surface layer. Hydrogen does not have the ability to form a satisfactory layer as shown by Bowden but oxygen and water vapor have the capability of forming the necessary surface film. Bowden* and coworkers have shown that in a vacuum of 10^{-10} Torr, the coefficient of friction of diamond sliding on diamond is of the order of 0.9 to 1 (figure 2-1).

d. Diamond Orientation

It is necessary to mount the diamond crystal in the bit so that the hardest portion of the diamond is presented to the direction of work. Long** reports that the setting of the hard vector orientation in high grade diamonds in a bit crown appreciably increases the drilling performance and life of the bit.

e. Diamond Size and Set

When the diamond is cast in the matrix so that a portion of the diamond protrudes from the matrix, it is called a surface set bit. The size of the diamonds normally used for surface set core bits ranges from 8/carat to 60/carat.

An impregnated bit is one in which the diamond particles are dispersed uniformly throughout a relatively soft matrix. During the operation of the drill, the abrasion of the rock chips continually wears away the softer matrix, exposing fresh diamonds. An impregnated bit is generally considered to be less efficient for core drilling than a surface bit.

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* Dr. F. P. Bowden, Function and Wear of Diamond in High Vacuum, Cavendish Laboratory, Cambridge, England.

** Long, Dr. Albert E. and C. B. Slawson, Report of Investigation 4853; Diamond Orientation in Diamond Bits, Bureau of Mines.

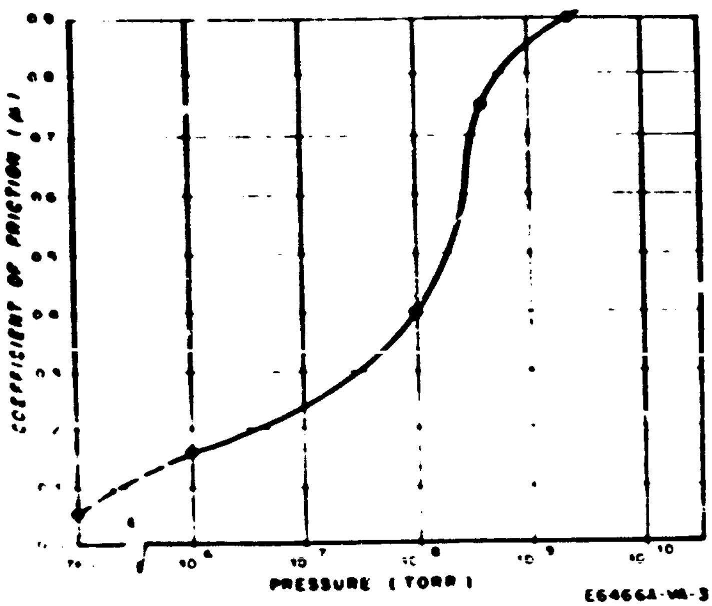

Figure 2-1. Equilibrium Value of Diamond Friction as a Function of Gas Pressure

2.1.2 Bit Development and Chip Removal

As noted in the introduction, rotary dry diamond drilling and chip removal were two of the priority areas for which feasibility was to be demonstrated during the first 120 days of the contract. Consequently, effort was immediately initiated on these areas and because of their fundamental importance has continued at a high level throughout the program.

Since there was no published record of a successful attempt to drill with a dry rotary diamond drill, it was necessary to initially evaluate the problems that exist with commercial drilling equipment and then to design a development program based on the state-of-the-art knowledge. Because of the urgency of the program, it was decided to initiate immediately both an empirical and an analytical program.

Commercial experience has shown that prompt chip removal from the cutting area is critical, since the bit binds and overheats if this is not accomplished. An analytical effort was undertaken at Westinghouse as well as at Arthur D. Little, Inc. to determine theoretically the cutting mechanisms involved, the fraction of the heat remaining in the rock, the amount that could be carried away as chips, and the amount that is transmitted to the bit.

Simultaneously, empirical efforts were initiated to determine the feasibility of drilling dry if chips could be removed, the design of auger flights to carry chips up and out of the hole, and the optimum design of the diamond bits to assist in the removal of the chips and to prolong the bit life.

2.1.2.1 Bit Development

By 1 December 1965, the feasibility of dry diamond drilling in ultra-high vacuum had been demonstrated by drilling approximately 6 inches into a basalt rock. The drilling was intermittent, allowing the bit to cool after every 30 seconds of drilling. Chip removal was excellent and no bit damage resulted.

Following the demonstration of feasibility, the bit tests continued with carefully instrumented tests which allowed the determination of matrix temperature, rpm, thrust, torque, penetration rate, and calorimetric measurements on specially constructed bits. Continued study of the problems of diamond setting resulted in a general improvement in diamond bit design.

In June of 1966, a water-cooled bit,which incorporated cubic gage stones and oriented octahedral face stones,drilled 123 inches in basalt. Because of limitations of the test drill system used, the maximum length of each stroke was approximately 8 inches. It is believed that, if the bit could have been allowed to cut continuously, the total length drilled would have been well in excess of that accomplished. Bits of this general design were delivered as a part of the drill system. Figures 2-2 and 2-3 show one of the bits built to this specification.

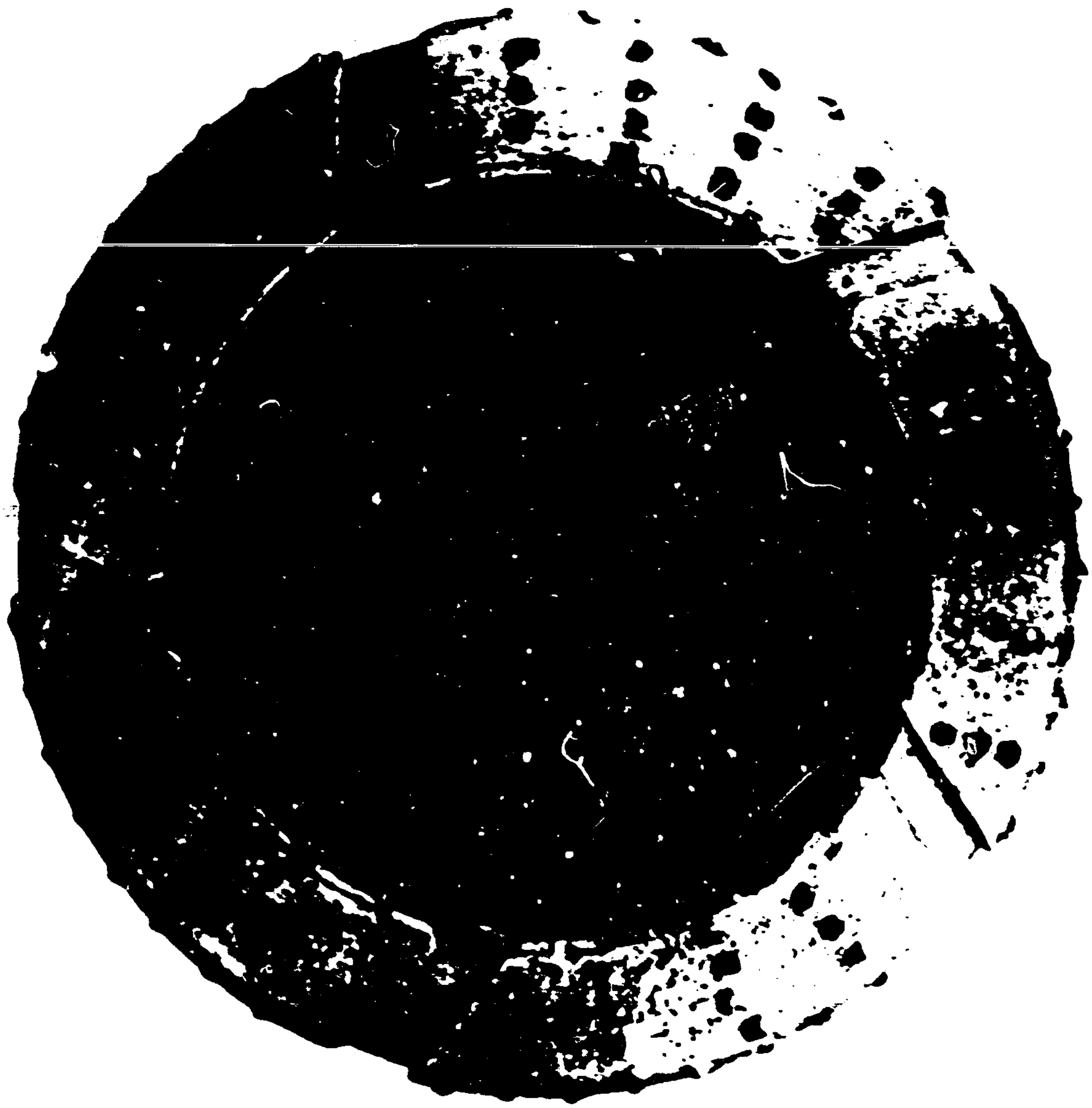

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Figure 2-2. Diamond Layout of a Delivered Bit

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Figure 2-3. Side View of a Delivered Bit

In the course of the experimental effort described briefly above, 34 diamond bits were manufactured and tested. Table 2-1 is a summary of the tests run and the results obtained. The details of these tests are presented in Appendix A.

The analytical effort that paralleled the experimental work just discussed drew heavily on the experimental results for guidance and verification. It can be shown on the basis of this work that approximately 80 percent of the total heat generated in drilling resides in the chips. Part of the residual heat remains in the rock and only a small portion of it is actually transmitted to the bit. It then follows that, if the chips can be quickly removed from the cutting area, the bit cooling required will be minimized. This analysis has led to the conclusion that, if the chips can be removed, there is a reasonable possibility that dry drilling can be accomplished with no bit cooling.

Tests run during the drill systems tests have verified tentatively the validity of this analysis. During these tests, one drill bit was used to drill dry into basalt. No internal coolant was used and drilling progressed normally to 22 inches where the bit failed mechanically (figure 2-4). Inspection of the bit showed only minor chipping of the face diamonds and normal wear on the remainder. The crown mechanical failure occured due to the seizing, of the bit as a result of a chip binding problem.

2.1.2.2 Chip Removal

The problem of chip removal is closely associated with drill bit design. Early bit tests relied on centrifugal force for chip removal. The feasibility of lifting chips out of the hole with auger flights was demonstrated as one of the priority items during the initial 120 days of the contract.

The chip removal problem is a two-fold one. It is, first, necessary to move the chips outward away from the drill bit toward the side of the hole and then to lift the chips to the top of the hole or to a point that they can be deposited into a chip basket. The former problem is a function of bit design and the latter is a function of the auger flight design.

TABLE 2-1

LIST OF BITS TESTED

Bit Number	Bit Design	Purpose of Experiment	Results	Reference: Monthly Progress Report	Reference: Appendix	Reference: Bit Identification in Appendix
1	Industrial-impregnated L/Y BH 12.	Feasibility of diamond drilling in basalt at earth ambient, chip removal by gravity and centrifugal force.	Showed that conventional bits can drill several inches - if cuttings are removed.	1	A	No. 1
2	Industrial-surface set L/Y BH 2	Same as No. 1	Same as No. 1	1	A	No. 2
3	Industrial-surface set L/Y BH 2	To check out procedure for vacuum drilling test Chips removed by centrifugal force.	Showed capability of drilling dry in 10^{-8} vacuum with chips removed by centrifugal force.	2	A	No. 1
4	Same as 3	To conduct high vacuum test. Chips removed by centrifugal force. 80% of kerf cutting.	Same as 3	2	A	No. 2
5	Special bit 30 auger flights	To test feasibility of auger flights for chip removal.	Indicated that with proper auger flight design chips could be removed.	2	B	•
6	Special bit "snow plow" diamond setting.	Earth ambient check out of equipment. Chip removal design.	Successfully removed chips.	3	A	•
7	Same as 6	Checkout of test equip at earth ambient.	Bit failed due to axial overloading.	3	A	3
8	Same as 6	Checkout of bit in manually controlled drill.	Bit cut unsatisfactorily to depth of 1 inch.	3	A	4
9	Same as 6 but with more [illegible]	Checkout of bit [illegible]	Bit cut satisfactorily [illegible]	3	A	5

	diamonds to withstand axial load.	trolled rig.					
10	Same as 9	Drill and remove chips in high vacuum.	Bit failed due to excessive axial pressure.	3	A	6	
11	Multiribbed impregnated face-60 diamonds on face.	Test of bit designs using auger flights for chip removal.	Bit failed under 400 lb thrust.	3	B	1 - (U1701)	
12	Same as 11	Same as 11	Bit failed after 0.537 inches.	3	B	5 - (U1702)	
13	Ribbed surface-set face - 150 diamonds on face.	Same as 11	Bit failed after 5.80 inches.	3	B	2 - (U1699)	
14	Same as 13	Same as 11	Bit failed after 4.75 inches.	3	B	6 - (U1700)	
15	Spiral surface set 127 diamonds on face.	Same as 11	Bit failed after 12.9 in.	3	B	4 - (U1164)	
17	Spiral-Surface set.	To gather more bit performance data and to test drilling techniques.	Bit failed after 13.05 in. Drill rig data collected.	4	A	U2879	
18	Same as 17	Same as 17	Bit failed due to drill equipment failure.	4	A	U2882	
19	Spiral surface set with additional ID and OD gage stones.	To check out equipment prior to high vacuum tests.	Equipment and bit were unsatisfactory.	4	B	U2883	
20	Same as 19	To satisfy feasibility require- [illegible]	4.5 inches cut in vacuum with [illegible]	4	B	U2881	

		[illegible] dry and remove chips in vacuum	[illegible] wear or damage to bit.				
21	Same as 19	To obtain information necessary to develop bit temperature measuring system.	Test terminated due to loose thermocouple and subsequent bit failure.	5	A	U4880	•
22	Same as 19	Same as 21	Thermocouple was satisfactory bit cut 11.5 inches (total of 16 in. see 20 above). Bit showed no damage or undue wear.	5	A	U4881	
23	Same as 19	Determine life of cooled bit, determine energy distribution during test.	Bit failed after 40 in. Rotary speed, torque, thrust, penetration rate and bit temp monitored.	7	A	•	
24	Same as 19	Same as 23	Bit defective (matrix bound)	8	•	•	
25	Same as 19	Same as 23	Bit defective (matrix bound)	8	•	•	
26	Same as 19	Same as 23	Bit failed after 35 in. temp and penetration rate monitored.	9	•	•	
27	Same as 19	Same as 23	Bit failed at 41-1/4 in. Bit was faulty. Penetration rate, rpm, thrust, coolant temp and flow rate measured.	11	•	•	
28	Same as 19	Same as 23	Bit failed after 123 in. at 8 in. intervals.	11	•	•	

			Measurements same as 27.			
29	Spiral surface set according to Spec 57893.	Test with drill system.	Crown cracked during attachment to core barrel. Faulty braze and excess torquing.	Appendix A Preacceptance Test.	-	-
30	Same as 29	Same as 29	I D gage stones pulled out during feathering.	Appendix A Preacceptance Test.	-	-
31	Same as 29	Same as 29	Same as 30	Appendix A Preacceptance Test.	-	-
32	Same as 29	Determine capability to drill dry without coolant.	Bit failed mechanically after 19 in. no appreciable diamond damage. Bit siezed due to inadequate chip removal.	Final Report Appendix A Preacceptance Test.	-	-
33	Same as 29	Same as 32	Drilled 3 inches - no failure.	Final Report Appendix A Preacceptance Test.	-	-
34	Same as 29	Same as 29	Bit c illed 6-1/2 in. Test stopped-no damage to bit-no problems.	Final Report Appendix A	-	-
35	Same as 29	Delivered with drill.	-	-	-	-
36	Same as 29	Delivered with drill.	-	-	-	-
37	Same as 29	Delivered with drill.	-	-	-	-

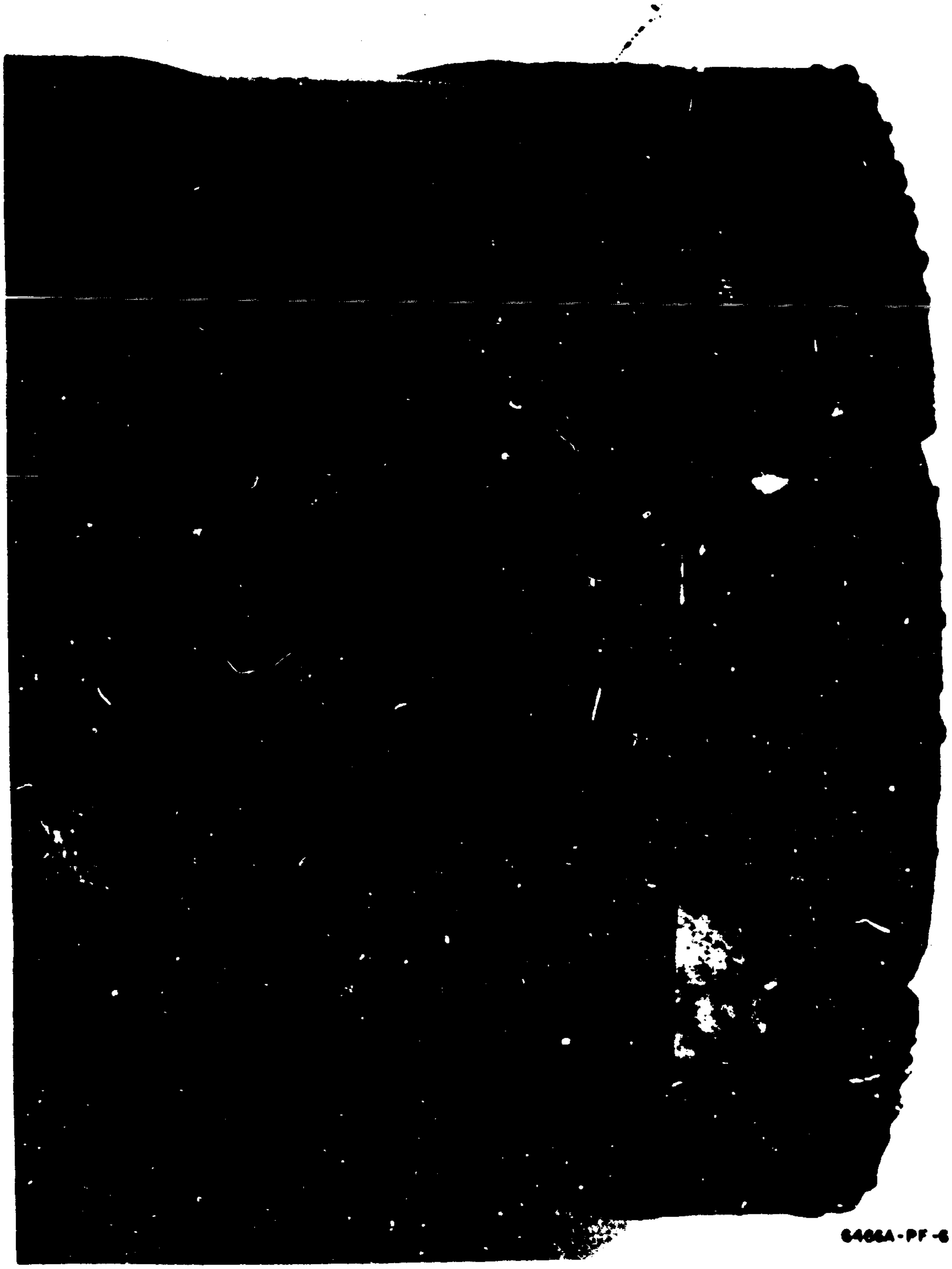

Figure 2-4. Bit Crown Failure During Dry Drilling

As illustrated in figure A-17 of Appendix A, the bit face has been designed so that the diamonds spiral toward the outer edge of the bit to give a "snow plow" action. Five channels are also designed into the bit to allow more freedom of movement of the chips to the outside.

Extensive auger flight tests at a number of rotational speeds indicated that at the drill speed of 1000 rpm a 40-degree pitch was more efficient than more shallow pitches. However, some evidence has shown that a tendency toward chip binding is increased with the higher pitches and a compromise of a 35-degree pitch was selected.

The original drill concept called for the capability of taking 5-foot cores. Density measurements on basalt chips indicated that the volume of chips obtained is approximately twice that of the core. The chip volume to core relationship dictated the design of a 15-foot core barrel and auger flight assembly. Five feet of the inner core barrel portion of the assembly would hold the core and 10-foot chip basket would retain the chips. Laboratory chip removal tests, using a plastic tube and simulated chips (Portland cement powder) showed that the auger flight was capable of lifting chips at least 9 feet. A marginal capability of depositing the chips in a chip basket was also demonstrated. A 15-foot chip lifting test was planned, but time and funds did not allow it to be carried out.

2.1.3 Results and Conclusions

The bits delivered as a part of the contract are constructed as shown in figures 2-2 and 2-3. The face diamonds are oriented octahedron crystal structure, exposed approximately 0.010 inch above the matrix and imbedded well past the midpoint of the crystal . The ID and OD gage stones are combination octahedron and dodecahedron crystal structures. The original design called for cubic diamonds in the gage positions. However, due to a shortage of cubic stones, the dodecahedron and octahedron crystals were substituted. Drilling tests run with bits of this design indicate that in steady drilling, the life time should be a minimum of 10 feet. Repeated stopping and starting will almost certainly shorten the life time as the result of the diamond burnishing during feathering and the increased danger of breaking diamonds. For better bit life, the initial collaring of the rock surface should be done with a bit other than that used for drilling the hole.

The chip removal design of the bits and the auger flight is felt to be marginally satisfactory. The chip removal tests are promising. In actual drilling, some binding due to chip agglomeration was experienced at depths of 22 inches. The ability to deposit chips in a chip basket 15 feet above the cutting surface has not been satisfactorily demonstrated. The system delivered utilizes the "snow plow" and chip passage design shown in figures 2-2 and 2-3 and five 35-degree auger flights on the sides of the bit and the core barrel.

In summary, diamond bit and core barrel auger flight designs show promise, but are not at this time considered suitable for a practical lunar drill design. Bit life time of up to 123 inches in basalt has been demonstrated with a bit design of this type. Auger flight efficiency has been demonstrated in loose chips up to 9 feet with marginal ability to place the chips in a chip basket.

2.1.4 Development Recommendations

It is recommended that a broad program be initiated in the immediate future to improve the bit cutting and chip removal techniques. Basic research into the mechanism by which diamonds cut should be accomplished. A study should be made of wear rates and wear mechanisms under a variety of conditions. At the present time, knowledge of these areas is almost pure speculation since very limited work has been done in these areas and much that has been done is not published in the open literature.

In parallel with the diamond research effort, a well balanced analytical and experimental program should be initiated to study chip removal techniques and the design of bits to take maximum advantage of theoretical information already available or that which will be developed under the diamond research program. For example, more exhaustive auger flight tests should be run to more clearly maximize auger flight angles, depth of the auger flights, clearance between the OD of the core barrel and the hole, etc. It is believed that an immediate improvement in bit life could be accomplished by utilizing properly set cubic gage stones and octahedron face stones set to cut along the "hard vector".

The question of diamond loading should also be investigated. Current commercial suppliers use a rule of thumb of 4 pounds per diamond. No satisfactory data has been found to indicate that this is an optimum figure, and if the variations in size, setting, and contact area of the stones in commercial bits are considered, it is clearly at best a questionable figure. The number of diamonds making contact at any one time is highly questionable in commercial bits because of relatively large variations in the matrix elevations as well as in the diamond protrusion above the matrix. If bits using selected and carefully set diamonds were developed, meaningful tests could be conducted to determine the proper loading to extend life time.

Concurrent with the above discussed studies, steps should be taken to improve the quality control practices of potential diamond bit suppliers.

Since diamond bit fabrication is an art rather than a science, steps must be taken to make the procedure more rigorous and methodical so that reproducible bits can be fabricated. Methods of determining logical tolerances and then monitoring them should be developed in conjunction and cooperation with the bit manufacturers. This is necessarily an educational process whereby the manufacturers must be made aware of the special problems facing the lunar drill in order to gain their cooperation.

2.2 CORE BARREL, DRILL ROD AND CHUCK DESIGN

2.2.1 Core Barrel Design

The core barrel is made up of two sections, an inner and outer core barrel; the outer core barrel drives the bit and removes the chips, the inner core barrel retains the core and the chips so that they can be brought to the surface. The outer core barrel is made up of three mating 5-foot sections as discussed in paragraph 2.1. Auger flights are ground on the outside of these sections for the purpose of lifting the chips from the drilling area to the top of the core barrel and the chip basket. These sections, which are constructed of steel and chromium finished on the outside, are designed to give sufficient rigidity to insure a straight hole and reduce bit run-out to an acceptable level. The chromium plating serves to increase wearability. The outer core barrels are made up of two tubes which are pressed together during final assembly; the outer tube carries the auger flights discussed above and the inner provides passageways for instrumentation leads and for the coolant water and steam of the bit thermal control system. The coolant and instrumentation passages mate with corresponding passages in the bit and the drill rods to allow continuity from the bit to the top of the drill string.

The three 5-foot sections of outer core barrel are designed to mate with threaded male and female joints. The threads are cut in a precision manner to insure that when the threads are tight the auger flights are smooth and continuous between connecting sections. O-ring and gasket seals are used to prevent leakage and electrical contact is maintained by pressing the mating connectors together. Alignment of the electrical contacts and the thermal control passages is assured by the precision mechanical threads.

The inner core barrel and chip basket assembly are designed to lock into place inside the lower outer core barrel section and is used to retain and recover the core and the chips. As noted in paragraph 2.1, the density of the chips is such that the volume of chips generated in cutting a core is approximately twice that of the core. The inner core barrel assembly is then divided into three parts - a core barrel 5 feet long and two 5-foot lengths of chip basket. Openings in the upper outer core barrel section allow the chips that have been augered to the top of the core barrel to enter the chip basket.

The lower end of the inner core barrel is provided with a mechanism which grasps the core as it is pulled upward. When the reduced cutting rate of the drill activates the "pull core" signal, the drill is stopped automatically. As the entire drill string is raised slightly, the core lifter, in the inner core barrel, grasps the core and breaks it free at the core-rock interface.

As discussed in the introduction, the entire drill string need not be removed to recover a core. Inner core barrel recovery is accomplished by dropping a "wireline" with a magnetic overshot attached down the drill string the magnetic overshot engages the top of the chip basket. As an upward force is exerted, the inner core barrel assembly is unlocked and drawn up the inside of the drill string. The replacement inner core barrel is lowered in the same manner and locked into place. Figure 2-5 is a sketch of the core lifter in place in the bit and around the core. Figure 2-6 shows an inner core barrel with a core in it and a core which has been removed.

2.2.2 Drill Rod Design

The drill rods are made of 5-foot lengths of extruded 6061 T-3 aluminum. Each rod has four holes for coolant passages (one liquid, 3 steam) and four channels for instrumentation. The coolant passages mate positively with male and female fittings. The rod sections are joined by an external coupling which utilizes guides and a segmented thread coupling much like breech block

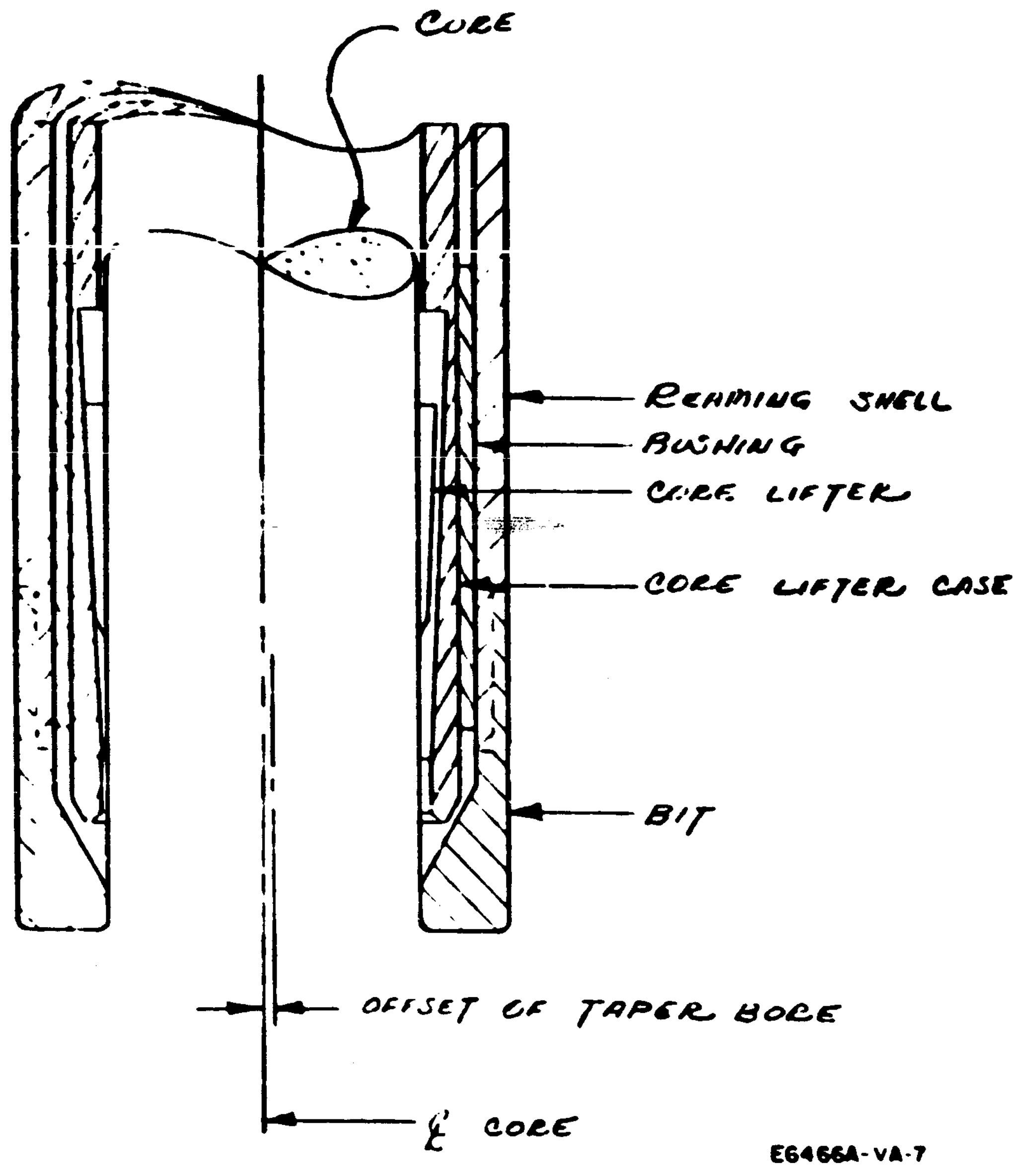

Figure 2-5. Lunar Drill Bit and Core Lifter

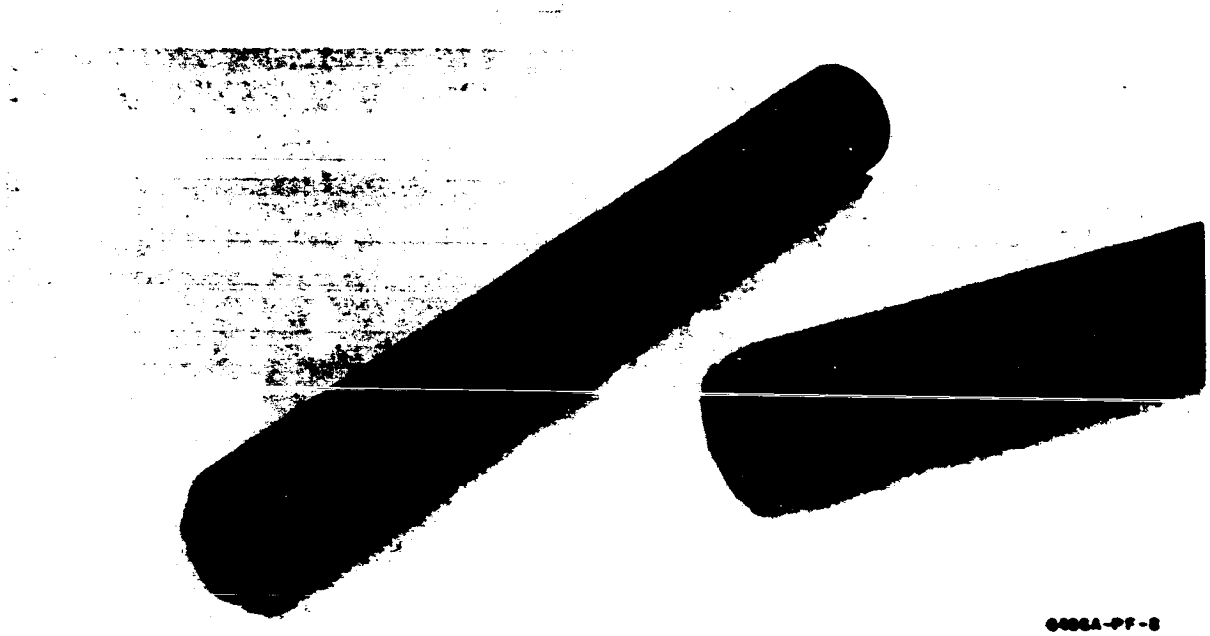

Figure 2-6. Inner Core Barrel and Core

locking mechanism. The contacts and coolant passages are mated and the coupling is given a partial turn firmly connecting the rods. The coolant passages rely on O-ring seals and the electrical contacts rely on mechanical pressure as in the core barrels. Figure 2-7 shows the end view of two drill rods and the coupling provisions.

2.2.3 Chuck Design

The chuck provides the interface between the drill rods, the gear box, and the rotary joint. Coolant and electrical signals are passed through the rotary joint into the chuck. The chuck mates with the gear box bull gear through a splined connection and connects to the drill rods in the same manner that the drill rods are connected together. An adapter is provided to allow the chuck to be used with the core barrels for the first 10 feet of drilling. Figure 2-8 shows the chuck.

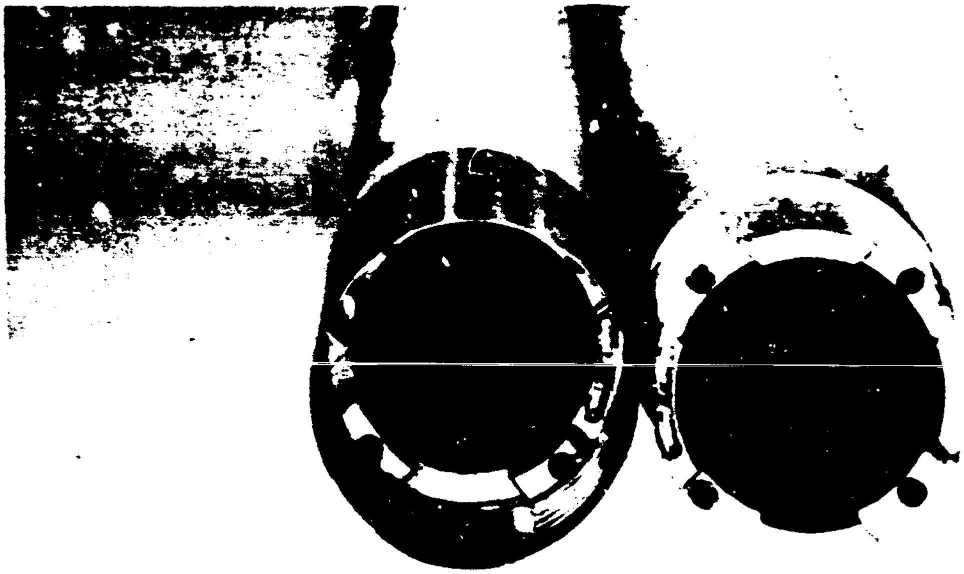

Figure 2-7. Drill Rod Coupling

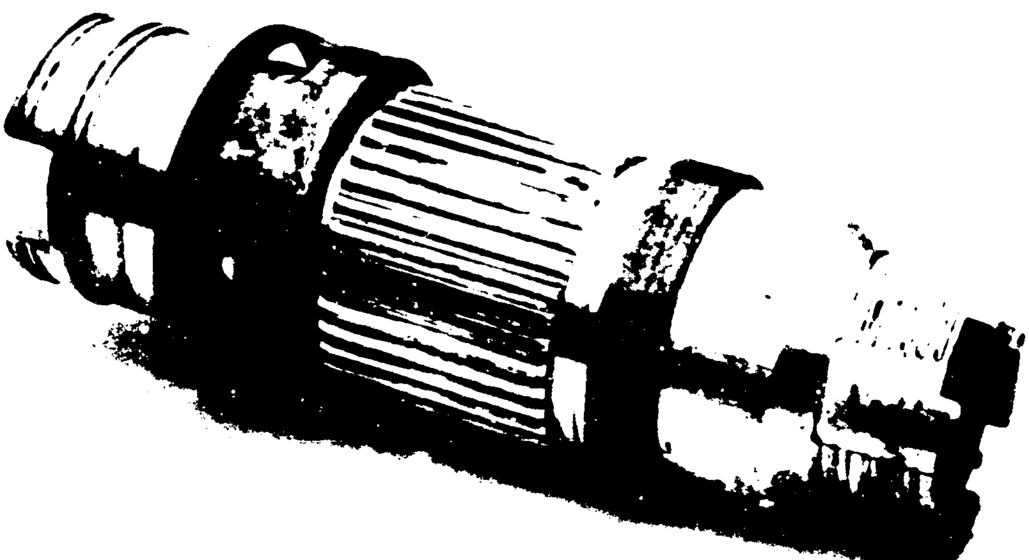

Figure 2-8. Chuck

2.2.4 Development Recommendations

2.2.4.1 Core Barrel

The outer core barrel fabrication method has resulted in serious problems in the final product. All core barrels that have been delivered to date have been crooked, out of round, and oversize. The present design of the outer core barrel incorporates two cylinders. The OD of the outer cylinder has the auger flights ground into it and the inner cylinder OD has the water, steam, and electrical lead passages milled into it. After the machining is finished to close tolerances, the two cylinders are mated by shrink fitting techniques and welding. Manufacturing development is recommended to allow a higher quality fabrication technique to be employed.

The inner core barrel core grasping mechanism (core lifter) has been demonstrated successfully from the core grasping viewpoint. There is some tendency for the core to break, not at the point of grasping, but at the rock-core interface. Extra rock beyond the diameter of the core may come along with it, and the core will not pass through the core lifter readily. The core therefore cannot be removed from the lifter section without breaking off the extra material. A reexamination of this design will be required to determine what is necessary for a clean core break.

The E.J. Longyear wireline concept provides for an overshot which locks over a spearhead whose base is attached through a latching device to the inner core barrel assembly. The force which springs the overshot clamp over the spearhead is supplied by the kinetic energy of lowering the overshot and the weight of the overshot. After the inner core barrel assembly is emptied, it is returned to its operating position. A special sleve is used on the overshot for this operation which forces the clamp open when the weight of the inner core barrel on the clamp is relieved by its reaching its operating position. The overshot then can be withdrawn. Recognizing that the reduced gravity on the moon would require a larger mass to perform the same clamping action a new overshot employing magnets was designed to keep weight to a minimum.

(figure 2-9). The principle of operation was to use the maximum force eserted by the magnets to lift the full core barrel assembly and to use a lesser force, created by introducing an air gap, to lower the inncer core barrel from the lower outer core barrel. The overshot was designed to have a maximum 85-pound pull for raising the full inner core barrel assembly and a 20-pound pull for lowering the empty core barrel and releasing the overshot. The dimensional restraints imposed by the drill string annulus and the degree of effectiveness of the available magnets resulted in a maximum 60-pound and a minimum 14-pound pull. Although a 60-pound pull is entirely adequate to lift the 28-pound weight of a loaded inner core barrel, it was not sufficient to pull the core barrel free of the effect of wedging of the inner core barrel during core break.

It is recommended that the overshot be redesigned to a form similar to the Longyear commercial design for a more positive core recovery despite the weight penalty.

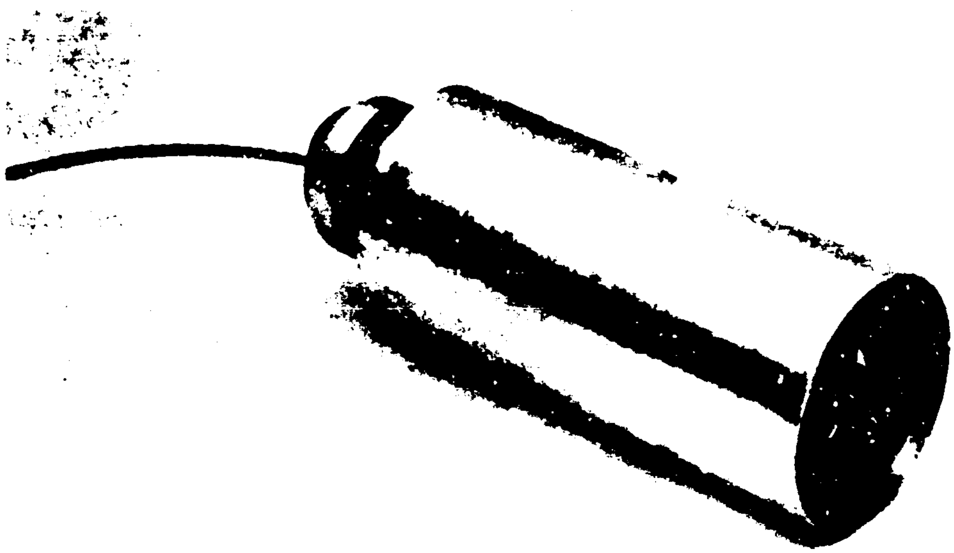

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Figure 2-9. Overshot

2.2.4.2 Drill Rod

The presently available drill rods have been statically pressure tested. However, no operational tests were required as a part of the contract. In the opinion of Westinghouse, the interconnection between the drill rods will not be reliable enough when used in long strings under field operating conditions. It is recommended that design studies and tests be carried out to determine what reliability improvements should be made.

The possibility of utilizing Lockalloy for drill rods to decrease weight and increase strength should be reexamined in the light of advances made in the technology over the past year.

2.3 CASING

Five feet of casing is provided to prevent cave-in during the first 5 feet of drilling since dust or rubble will most likely be encountered. The casing is furnished in five 1-foot sections which are threaded to form one continuous 5-foot length A diamond crown is provided on the first section and auger flights are milled on the outside of the casing. The first section mates mechanically with the drill string diamond coring bit and the casing is driven through this connection. When the casing has been driven to the 5-foot depth, the drill string is retracted slightly, placed in the rotational mode and advanced. The mechanical connectors on the casing bit are cut off by the diamond bit and drilling continues normally beyond the casing depth. Figure 2-10 shows the casing bit and figure 2-11 shows an end view of the coring bit installed inside the casing bit. There has been no operational testing of the casing bit design. Testing should be performed to determine the adequacy of the casing design.

2.4 ROTARY JOINT DESIGN

2.4.1 General

The rotary joint is necessary to provide coolant to the rotating drill string and bit as well as to provide a means of transmitting instrumentation signals from the drill bit to the monitoring equipment. The rotary joint attaches to

Figure 2-10. Casing

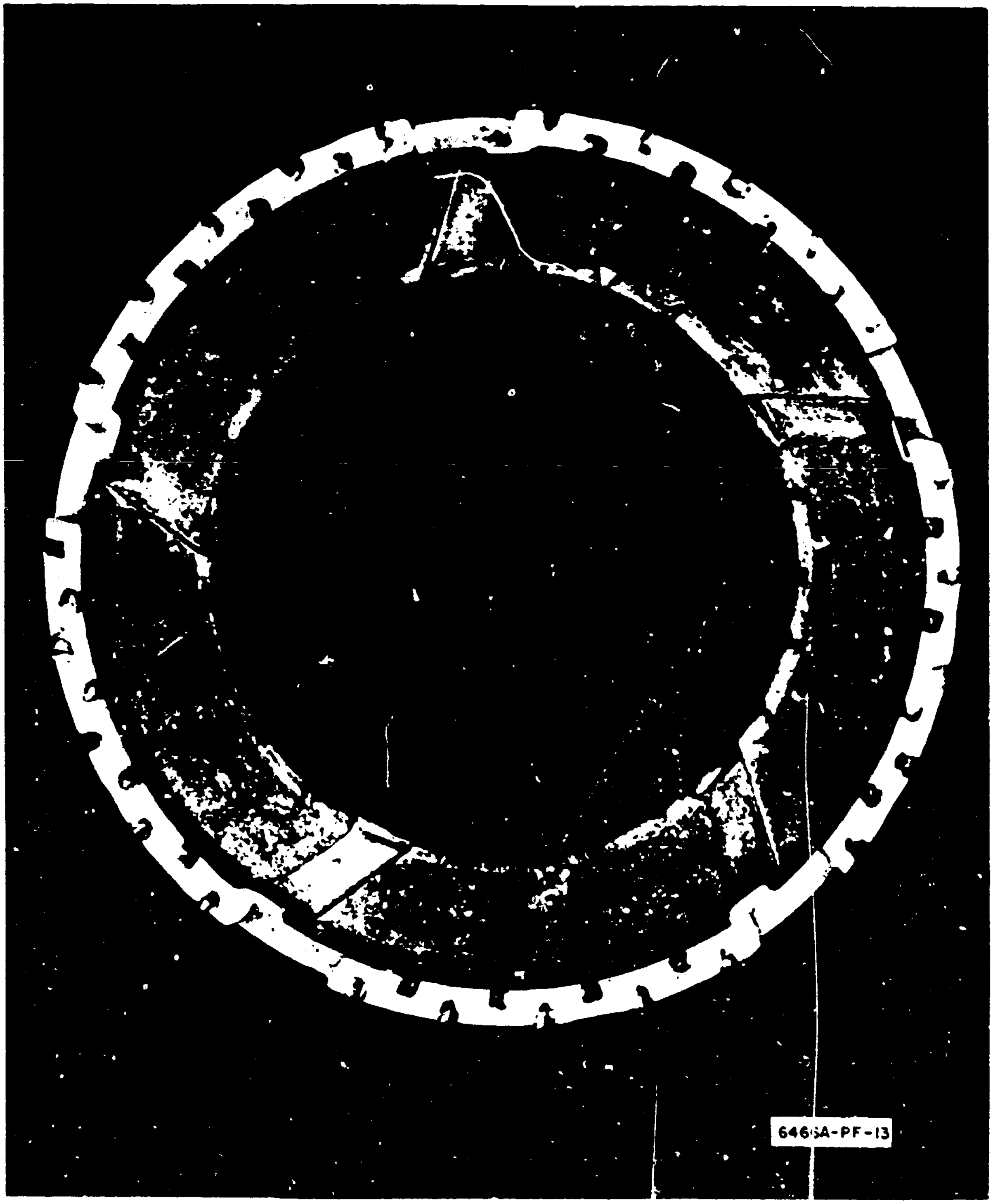


Figure 2-11. Casing Installed on Coring Bit

the top of the chuck and connects to the bit radiator and control panel on one end and the drill string coolant channels and bit instrumentation on the other. Modification of a standard rotary seal is used for the water and steam transmission and a rotary transformer has been incorporated for the transmission of the instrumentation signals. Figure 2-12 shows the rotary joint.

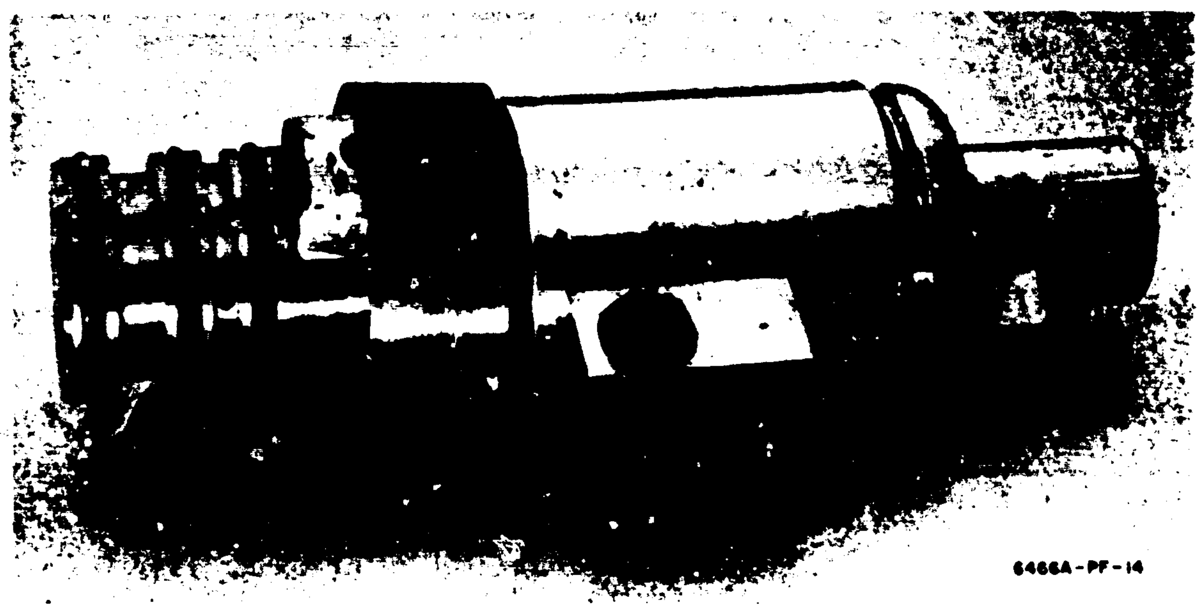


Figure 2-12. Rotary Joint

2.4.2 Feasibility Tests

Since the rotary joint was vital to the operation of the lunar drill concept as originally proposed, feasibility demonstration of the rotary joint during the first 120 days of the contract was a contractual requirement as discussed in the Introduction. The feasibility tests were conducted using a Type E rotary joint manufactured by the Barco Manufacturing Company. This joint was modified by the addition of a teflon O-ring to provide a static seal compatible with the vacuum environment.

The rotary joint was rotated at 840 rpm for a minimum of 30 minutes with an internal pressure of 250 psi and ambient pressures of 200 microns and 1.6×10^{-4} Torr. The major leakage rate was 0.85 gram/hour with an observable leakage taking place only at the beginning of vacuum chamber pumpdown. No leakage or ice formation was observed and visual examination of the dynamic seal showed no deterioration due to ice. This test is discussed in detail in Appendix B.

2.4.3 Development Tests

Since the rotary seal depends upon a slight coolant leakage for the lubrication of the seal and since there may be periods during the operation of the lunar drill in which no water or steam will be passed through the rotary joint, it was anticipated that excessive wear to the seal face might be experienced. It was felt that this problem might be eliminated by replacing the carbon seal with a solid lubricant gallium-indium-tungsten diselenide seal. Vacuum tests similar to those described in paragraph 2.4.2 were carried out on this seal which was installed in a Type E Barco rotary joint. The solid lubricant seal showed excessive wear and it was decided to use the standard graphite seal.

2.4.4 Acceptance Test

The acceptance test showed that the rotary seal appears to be adequate although the mechanical design of the housing and manufacturing techniques must be improved.

The seal was subjected to preacceptance testing and acceptance testing totaling 106 hours of static testing in earth ambients, 26 hours of static testing under vacuum conditions and 31.5 hours of rotation under vacuum conditions. The testing was interrupted by instrumentation and test equipment failures and by rotary joint design and manufacturing problems. The mechanical design problems were isolated to the bearing and seal, rotary joint housing interference and seal bellows-rotary joint attachment problems. The acceptance test data was valid up to 16 hours of operation at which time there was a major loss of coolant due to a combination of the seal bellows coming loose from the rotary joint housing and high temperature created by the clearance problems. At the time of the termination of the test, the seal appeared to be in good condition. Appendix B provides the details of the rotary joint.

2.4.5 Development Recommendations

In view of the results described above, it is recommended that further development be undertaken to improve the bellows seal to the rotary housing and to change the design to provide adequate internal clearances.

If it is proved certain through the bit development studies that bit coolant is not required, it will be possible to eliminate the rotary joint.

2.5 DRILL BIT THERMAL CONTROL SYSTEM

2.5.1 Requirement

Thermal control of the drill bit was a part of the proposed Westinghouse lunar drill design concept. The demonstration of feasibility of the proposed thermal control system was part of the priority requirements for the first 120 days of the contract.

2.5.2 Feasibility Test

Although in the proposal the initial estimate of heat to be dissipated during the drilling operation was approximately 3 kW, analyses carried out at Westinghouse and by Arthur D. Little, Inc. indicated that the probable thermal load which would be required to be dissipated from the drill bit and drill string would be approximately 1 kW. This figure was later verified by empirical measurements of the power utilized in drilling and calorimetric measurements of the heat taken out of the bit by a circulating fluid. Appendix C contains the Arthur D. Little report as well as the Westinghouse calculations and test information upon which the design of the bit thermal control system is based.

Consequently, the feasibility test was planned to show removal of 1 kW from a bit blank. The purpose of the feasibility test was two fold. First, it was to show that a thermal control manifold concept such as that proposed could remove at least 1 kW of heat and, secondly, that the design was such that vapor lock would not occur. The test setup for the feasibility demonstration is shown in figure 2-13. Heat was applied to the system at the bit blank and removed through a water-cooled condenser. The feasibility demonstration showed that 1 kW of heat could be removed satisfactorily by the use of this system. Appendices D and E discuss the Thermal Control Subsystem design and the feasibility test.

2.5.3 System Design

The drill coolant system for the Westinghouse lunar drill is comprised of a radiator, rotary joint, the other drill string coolant passages, and the

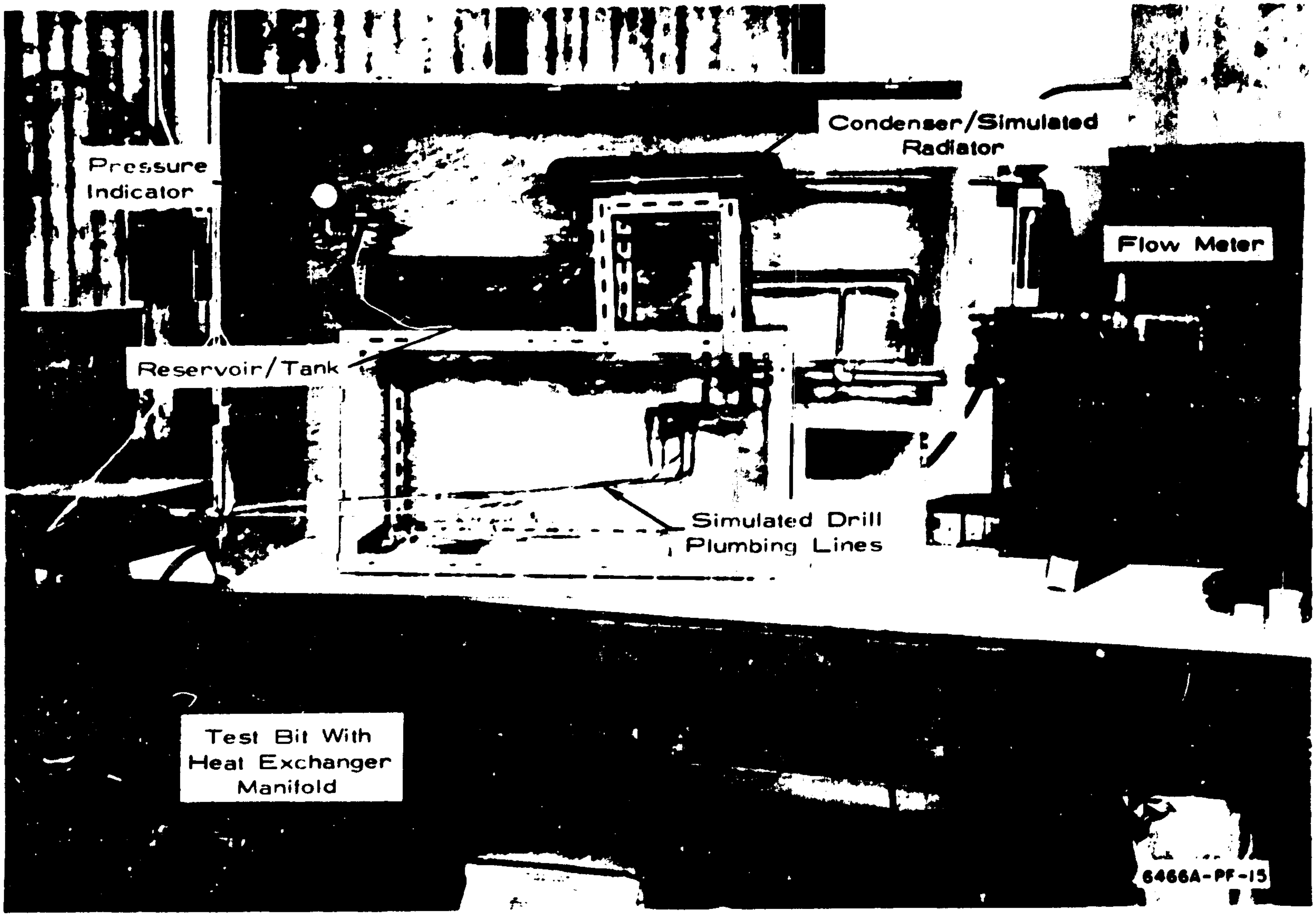


Figure 2-13. Thermal Control Feasibility Test Setup

bit manifold. The system is closed and operates in a fashion similar to conventional steam heating. The drill manifold acts as a boiler. Steam is forced up the passages to the condenser where cooling takes place and the condensation is fed back to the drill bit. A metering and valving system has been included to control the amount of water in the down-hole component in the lunar environment and the quantity of coolant lost during drill string additions.

The system has a rotary joint and drill string sections designed to handle a 3-kW load at 390°F. However, after the design of these components was frozen, it was decided to operate the engineering model at 212°F in order to give added protection to the drill bit. Consequently, the condenser lines, etc are designed for a thermal load of 800 watts at 212°F. Even through the down-hole components are off-optimum for this thermal load and operating temperatures, sufficient flow of coolant should be delivered to the drill bit. Since this system has not been thoroughly tested under dynamic conditions, an external coolant pump has been furnished as part of the system. This external pump will allow the coolant to be forced through the system in case of malfunction of the system as designed.

2.5.4 Development Recommendations

As indicated later in this section, extensive studies on bit design and cutting removal should be carried out to determine the necessity of providing a thermal control system for the drill bit. If these tests should show that such a thermal control system is necessary, then additional studies should be made,using the delivered equipment to determine the efficiency of the system which has been designed and to determine the changes which might be necessary to improve its operation. Since the system has not been thoroughly tested under drilling conditions, the first step should be a laboratory evaluation of the system followed by redesign and upgrading as necessary.

2.6 DRIVE MECHANISM

2.6.1 Drive Mechanism Design

The drive mechanism must perform three primary functions:

- **Transmit torque from the motor to the drill string**
- **Advance and retract the drill string**
- **Provide power to operate the hoist to raise and lower the inner core barrel**

These three functions are performed through the integrated gear box and the hysteresis clutch mechanisms.

2.6.1.1 Gear Box Assembly

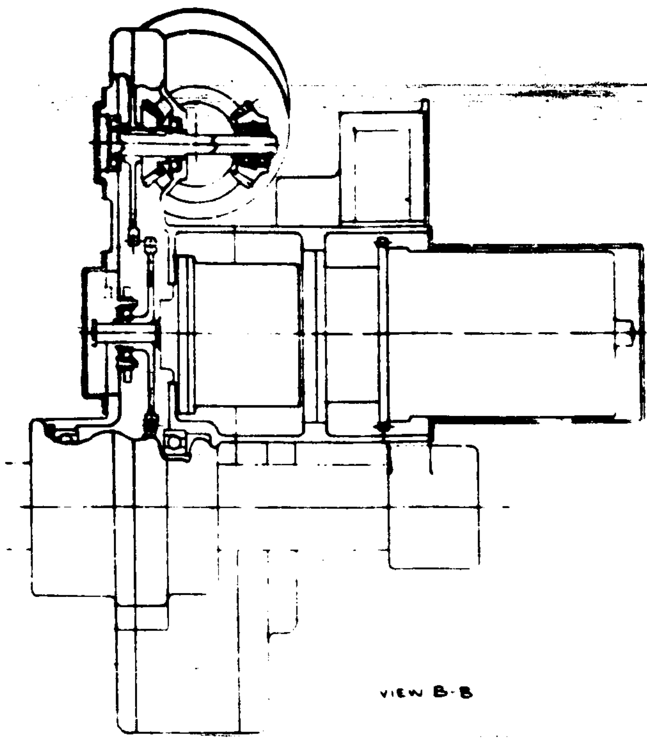
The gear box assembly provides a neutral position and two forward drill string rotational speeds of 200 and 1000 rpm from the nominal 6000-rpm input from the motor. The 1000-rpm rate is used for normal drilling, and the 200-rpm rate is provided for emergency high torque operation. The gear box is designed to deliver 60 foot-pounds under normal operation and 300 foot-pounds at the 200-rpm speed.

The gear case is of SAE 356-76 aluminum construction to conserve weight. The gears are A151 9310 vacuum melt steel with a carburized case depth of .025 - .035 inch. The gear train is lubricated by transfer from solid lubricant idler gears and the bearings are lubricated by solid lubricant ball retainers.

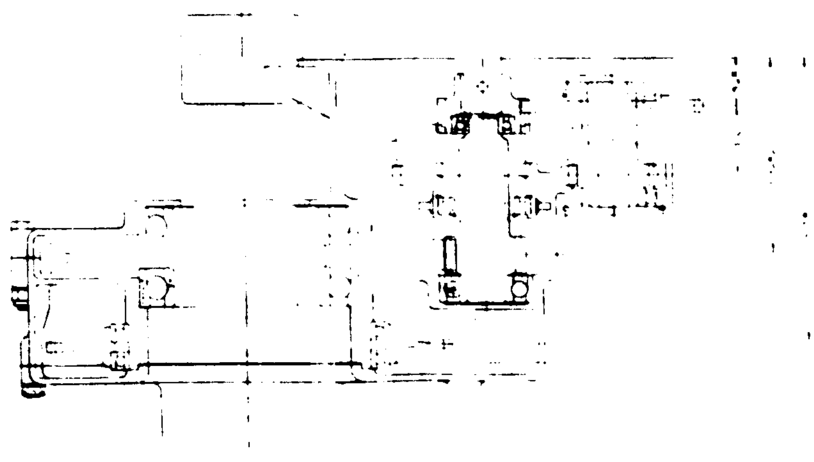
Figure 2-14, is a layout drawing of the gear box. Figure 2-15 depicts the gearbox assembly with the air-cooled motor mounted to it.

2.6.1.2 Hysteresis Clutch Mechanism

The hysteresis clutch is used to drive a 160-to-1 harmonic drive which moves the drill string in the vertical direction, raises or lowers the inner core barrel assembly through the hoist mechanism, and provides the core breaking force to the drill string. Figure 2-16 is a layout drawing of the hysteresis clutch assembly. It is located in the metal can on top of the gearbox case immediately behind the left-hand ball screw (see figure 2-8). A manual gear shift lever



VIEW B-B



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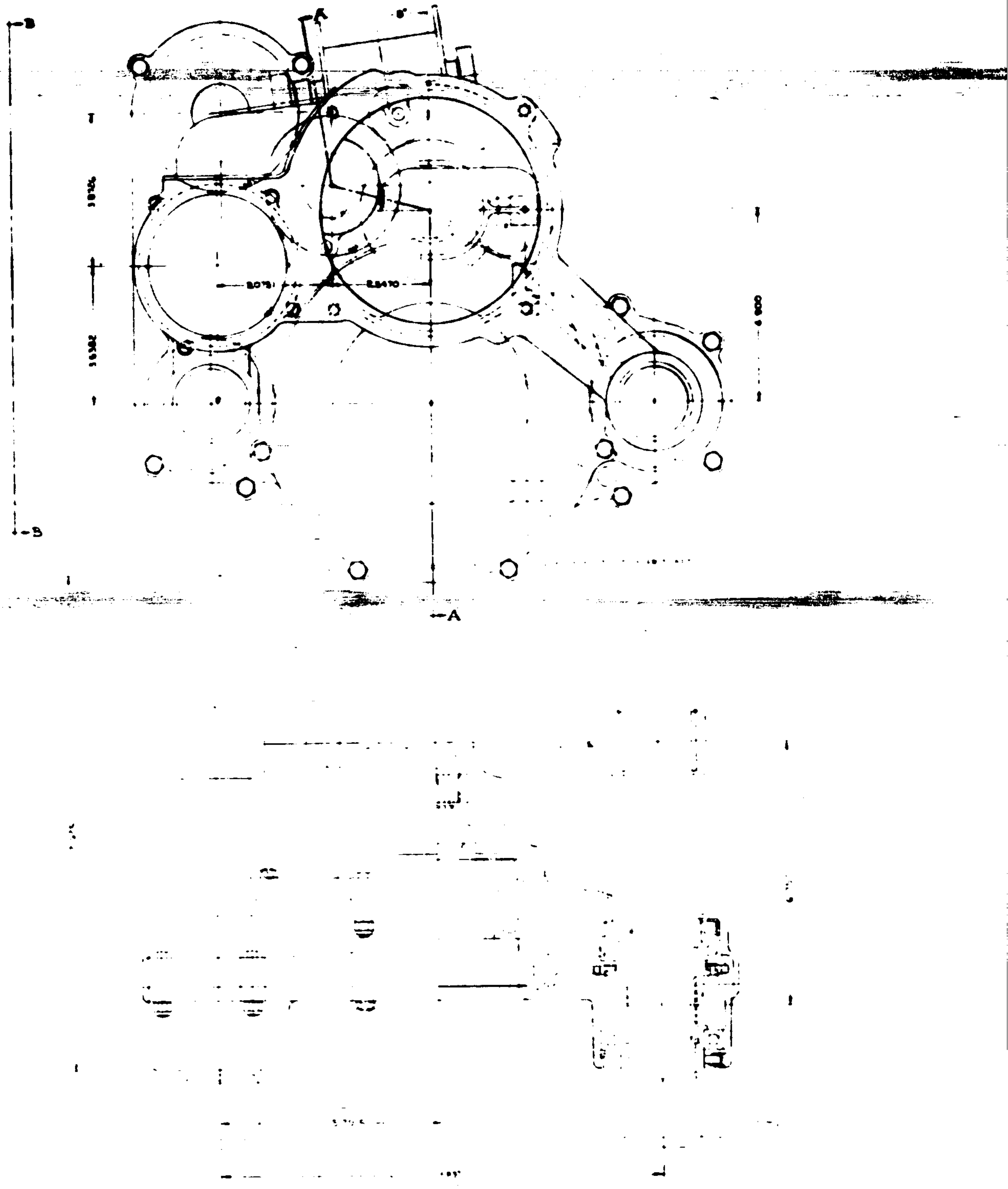


Figure 2-14. Drive Mechanism Layout

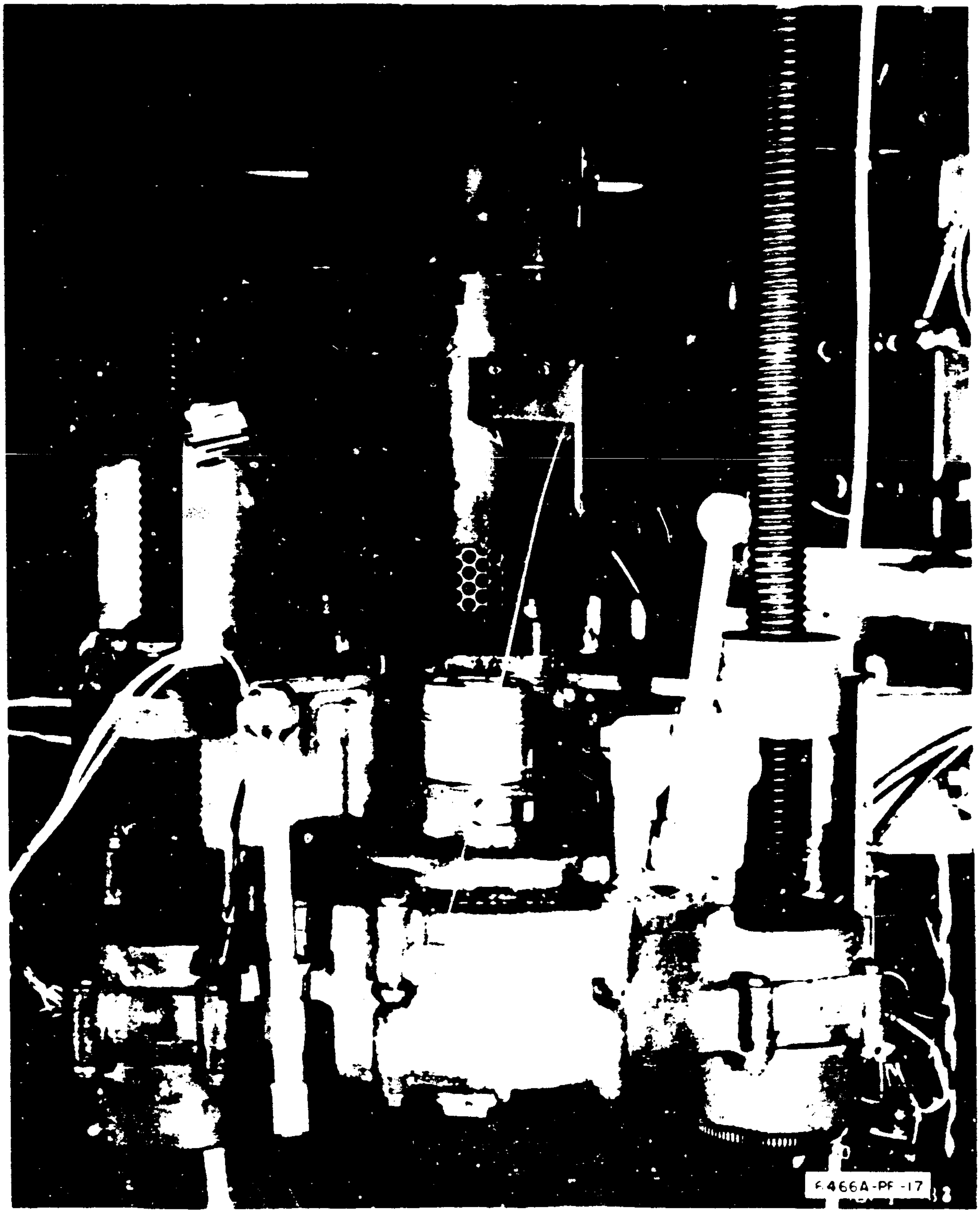


Figure 2-15 Gearbox with Motor Mounted

is provided to apply the output of the harmonic drive to the hoist or the ball screws. Sufficient speed control is provided to permit advance or retraction rates from 1/4 - 4 inches/minute and hoisting and lowering rates of the inner core barrel from 0 - 7 1/6 inches/minute.

2.6.1.3 Ball Screws

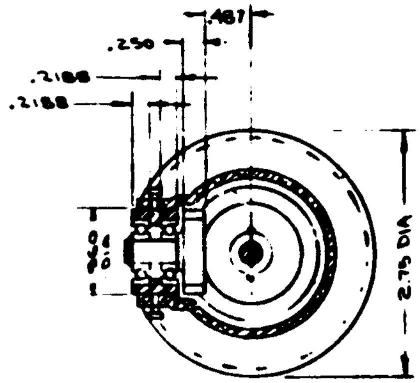
The steel ball screws are designed to allow a large mechanical advantage between the hysteresis clutch and the drive mechanism. The ball screw assembly is basically a conventional design, but the screws are hollow to conserve weight. The bearing surfaces are lubricated by a molybdenum disulfide coating and are kept clean by special nylon wipers. A downward force of 400 pounds for drilling and an upward force of 2000 pounds for core breaking can be applied. Figure 2-14 shows the ball screws supporting the gear box assembly.

2.6.2 Solid Lubrication

The analysis of the requirements for the gearbox and other mechanical parts to operate in a vacuum, the weight restraint, the possible gearbox oil sealing difficulties, the high motor input speeds, and the possibility of high gear and bearing temperatures indicated that the best probability of operational success lay in the use of solid lubricants.

The Westinghouse Research Center, Churchill, Pennsylvania, a forerunner in solid lubricant technology, was given a subcontract to modify standard high quality bearings to accept solid lubricant ball retainers and to provide solid lubricant gear blanks to be made into idler gears which would lubricate the gearing through a transfer mechanism.

The experience with solid lubricant bearings has been extensive in laboratory applications. Experience had shown that bearing lives in excess of 300 hours, at 10,500 rpm and under loads similar to those expected in the gearbox, can be achieved. Vacuum operation appeared to have little effect on bearing life. However, extrapolating laboratory experience to a gear box environment was considered to have some risk.



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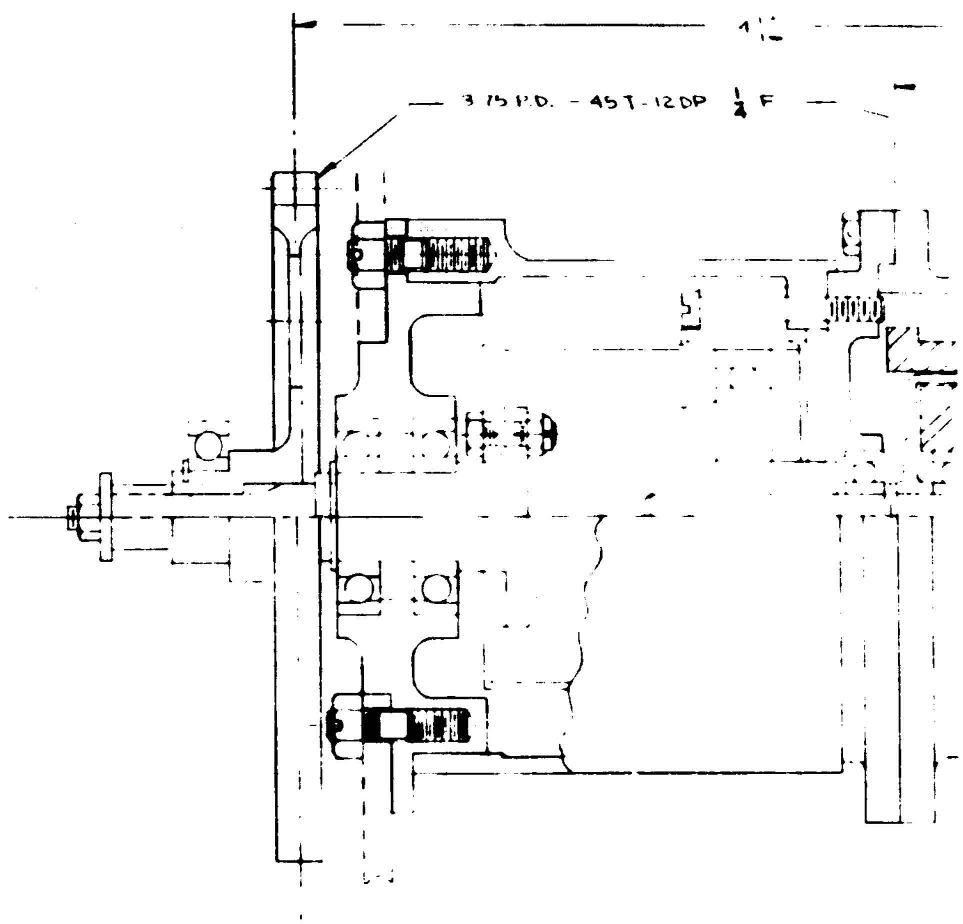

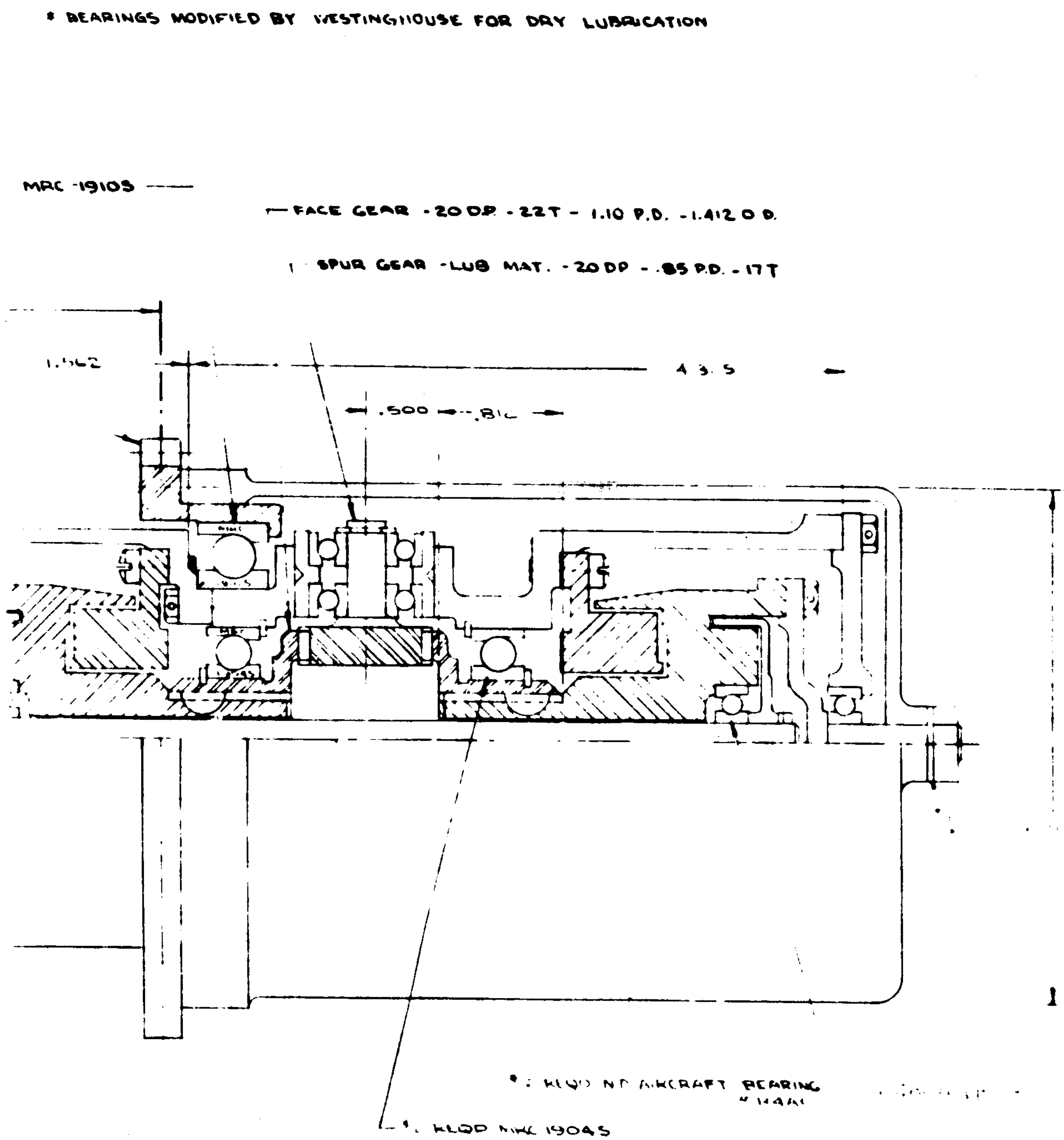

Figure 2-16 Hysteresis Clutch Assembly

The experience with solid lubricant idler gears was not as extensive, and this experience was attained with relatively slower operational speeds, different gear designs, and loads.

A development testing program was recommended by the supplier, but due to funding and schedule restraints it was decided to proceed with the bearing and gear lubricating designs based upon the available experience.

Solid lubricated bearings are noisier during operation than oil or grease lubricated units. The absence of the fluid cushion film and the greater clearances required to accommodate the thicker solid films and wear debris are the reasons for the noisy operation. It is important that the solid lubricated bearings have a degree of preload to insure that all of the balls are loaded continuously and are not free to chatter and skid. The preload for each bearing must be determined on the basis of its operating conditions.

Thermal expansion of the solid lubricant bearing design becomes a problem only if the frictional heat raises the bearing temperatures to a point where the clearances are lost. The amount of frictional heat generated will differ from bearing to bearing depending upon the loads, speed, and the availability of a heat sink. The clearances provided were expected to be adequate up to 600°F.

The loading of the idler gear has been determined to be:

$$L = \frac{W \times \sqrt[4]{S}}{DP \times C}$$

where:

C = Constant = .04

DP = Diametrical pitch of the idler gun

L = Applied load of the idler gear in pounds

W = Width of idler gear in inches (contact width)

$S = \frac{PD}{2}$ in inches x rpm (PD = pitch diameter)

Since the method by which solid lubricants function is that of sacrificial wear, there is a chance always of a buildup of wear debris. For the major part, the material worn in one spot will recoat at another location but some will end up as a loose powder. In laboratory tests at 10,500-rpm speeds, 100-pound axial and thrust loads, 1 to 2 grams of powder may be collected after 100 hours of operation. If the debris does not leave the bearing but lays in the ball path, it will cause a roughness which will cause excessive mechanical shock and shorten the retainer life. The amount of wear debris which would cause failure in 200 hours of operation, the goal for the gear box bearing design, is a function of the bearing size, clearance and loading.

Interface difficulties and manufacturing tolerance buildups resulted in low preloading of the bearings.

Several bearings were damaged due to improper handling during installation and disassembly operations and as secondary failures resulting from contamination by metal chips from external sources.

The solid lubricant idler gears which operated at the higher gear box speeds failed repeatedly while those operating at or below 1000 rpm operated as designed. The failures of the high speed idler may be attributed partly to the material, the loading, their type of mounting and the generous clearance of the gearing at normal ambients. The clearances were the results of allowing for the linear expansion of the gears over the design range of -40° to 165°F and the compensation for the differences in the coefficient of linear expansion between the steel gears and the aluminum gearbox over that range.

Figure 2-17 shows the condition of a high speed idler after the 15-minute run of the gearbox in a vacuum of 10^{-5} Torr. The bearing failure is a secondary failure.

The high speed idlers were not replaced in the assembled drill system on the separate gear box. The high speed gears in the assembly system were lubricated periodically with Apiezon H grease containing zinc oxide and molybdenum disulfide in proportions by volume of 8-3-1 respectively.

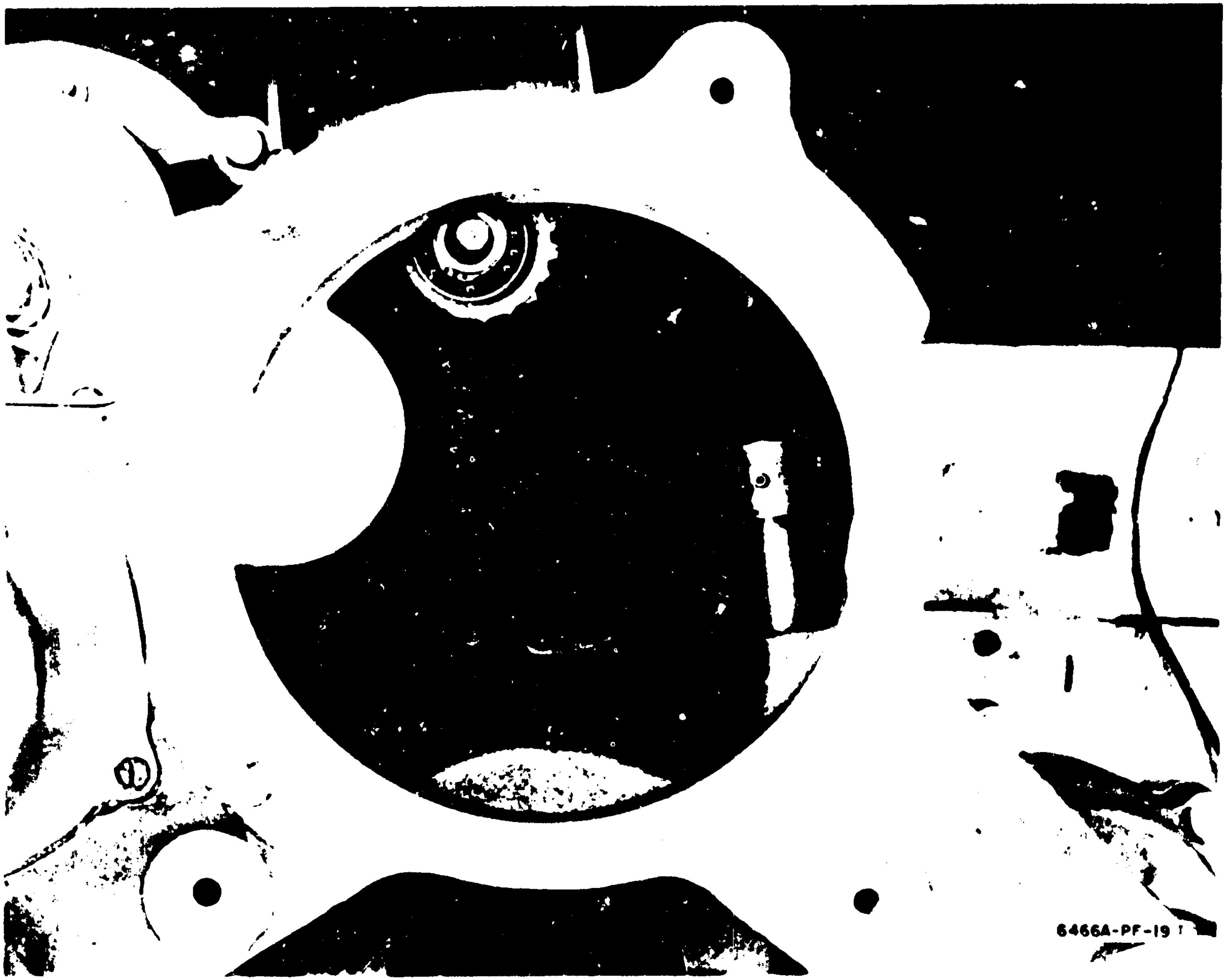

Figure 2-17 Failed Gearbox Idler Gear

Westinghouse Central Research has evolved a design of a new idler gear and mount consisting of a porous ployamide gear which permits a low vapor pressure oil to be bled from a central oil reservoir. This design was not manufactured due to funding and schedule restraints.

The mechanical parts lubricated with a form of solid lubricant are:

Gearbox and Hysteresis Clutch

1 - Gears - phosphated and electrofilmed (molybdenum disulphide)

2 - Idler Gears (6) - silver - mercury - teflon composite

3 - Bearings (41) - gallium indium - tungsten diselinide composite

4 - Bearings (2) - gold plated

5 - Splines - phosphated and electrofilmed

6 - Harmonic Drive

a. Wave generator - gold plate over molybdenum disulphide

b. Wave generator bearing - Apiezon H grease and 20% by weight of molybdenum disulphide

7 - Screws - phosphated and electrofilmed

8 - Screw wipers - nylon

9 - Bushings - silver - mercury - teflon composite

2.6.3 Operational Experience

Approximately 35 hours of operation have been accumulated on the box. During this time, the major failures have been idler gear and bearing failures. In general, the bearings have operated satisfactorily despite low preload. No gearbox failures have occurred in the conventional gearing, although one jack shaft cont ning an integral gear was replaced due to slightly undersize splines causing bble in a gear with the mating splines. The hysteresis clutch has exhibited no failures.

2.6.4 Development Recommendations

The basic design of the gearbox appears to be sound. Some development should be undertaken to arrive at a design which can function as required under the full range of lunar ambient temperatures.

The use of solid lubricant bearings and gears should be reviewed and tested further. Studies of the possibilities of a sealed gear box and of either low vapor pressure or replaceable lubricants usage should be made.

The hysteresis clutch should be modified to include an angular velocity sensor which is driven by the harmonic drive input shaft. The present sensor used for feed rate control is a dc tachometer driven through a stepup gear train tied to a ball screw nut. Since the ball screw nut turns at 1.25 rpm for a 1/4-inch/minute feed rate and at a maximum speed of 20 rpm for a 4-inch/minute feed rate, a large stepup ratio is required.

2.7 MOTOR

2.7.1 Motor Design

The motor design selected for the Westinghouse lunar drill system is a 100-volt dc motor capable of delivering 60 inch-pounds at the normal operating shaft speed of 6000 rpm. The motor is sealed for vacuum operation. The motor is pressurized to 50 psi with nitrogen and fluid-cooled with U-CON (polyalkaline glycol) oil. Pressurization is necessary to reduce cavitation conditions at the coolant pump which is located at the base of the motor case.

Heat is removed from the motor armature in two ways. The pressurized gas carries some heat to the motor case by convection. The coolant flows through coolant tubes, which are wound around the case to remove this heat and the stator heat and carry it to the radiator. The majority of the heat is removed by the circulation of the coolant fluid through the motor itself. The coolant enters the top of the motor and is pumped through the hollow rotor shaft to a sump at the base of the motor case. The pump, located in bottom of the sump, was a simple impeller designed to force the coolant out of the sump, through the radiator and back to the motor. Figure 2-18 is a sketch of the motor cross section and figure 2-19 is an end view of the assembled motor.

2.7.2 Operational Experience

A limited amount of operational data has been gathered on the motor. However, during this time, a number of problem areas have arisen. Because of compromises which were made in the design in order to reduce weight and size, commutator length and brush area are smaller than would normally be expected for a motor of this power rating. This, combined with the apparent deleterious effect of the U-CON, has resulted in unusual mechanical wear on the commutator. It is estimated that the maximum operational life of the motor is 8 to 10 hours before refurbishing of the commutator will be necessary. In addition to contributing to the commutator and brush problem, there is evidence that the U-CON may attack other materials internal to the motor. However, this latter possibility has not been definitely confirmed.

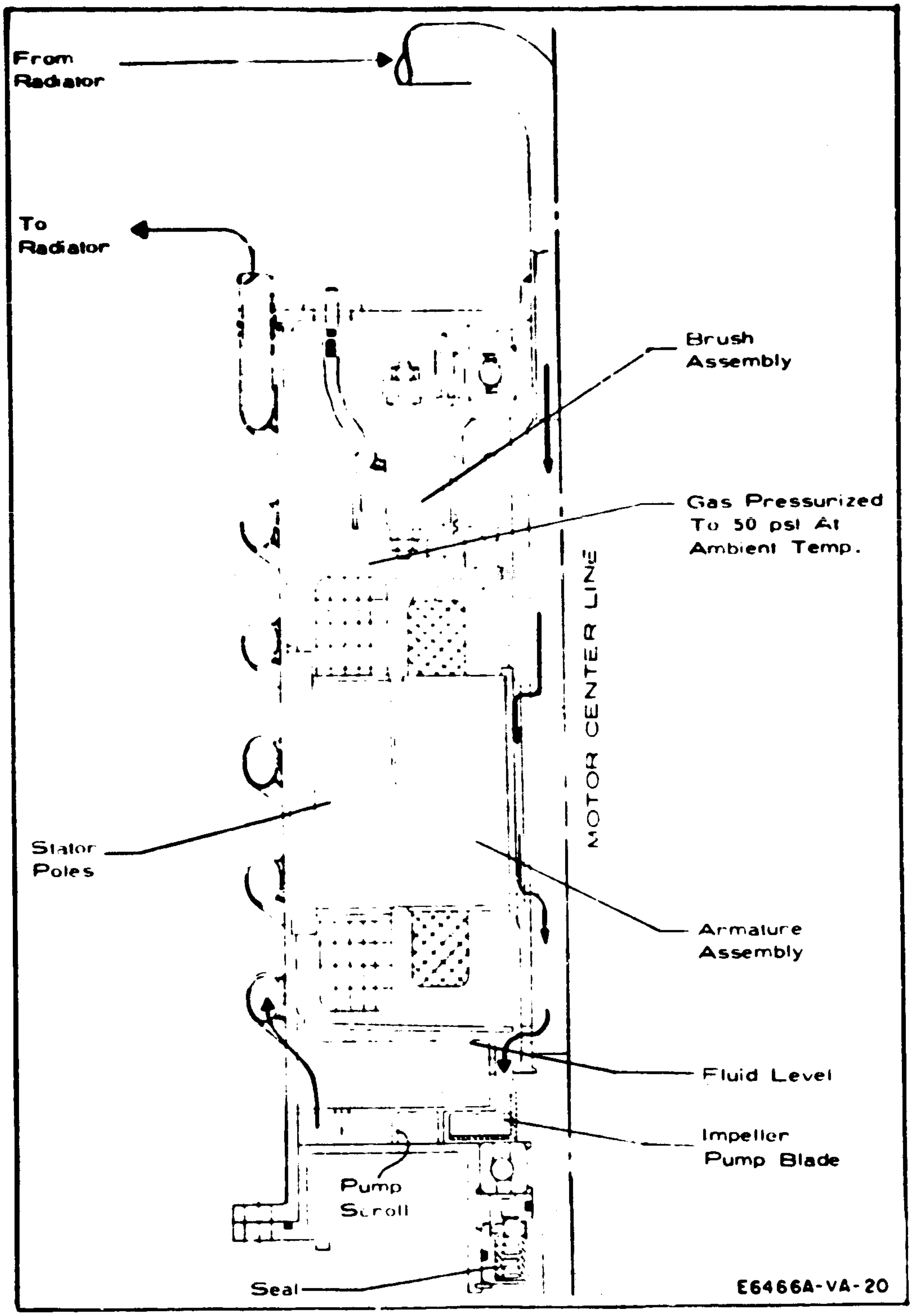

Figure 2-18. Drill Motor, Cross Section View

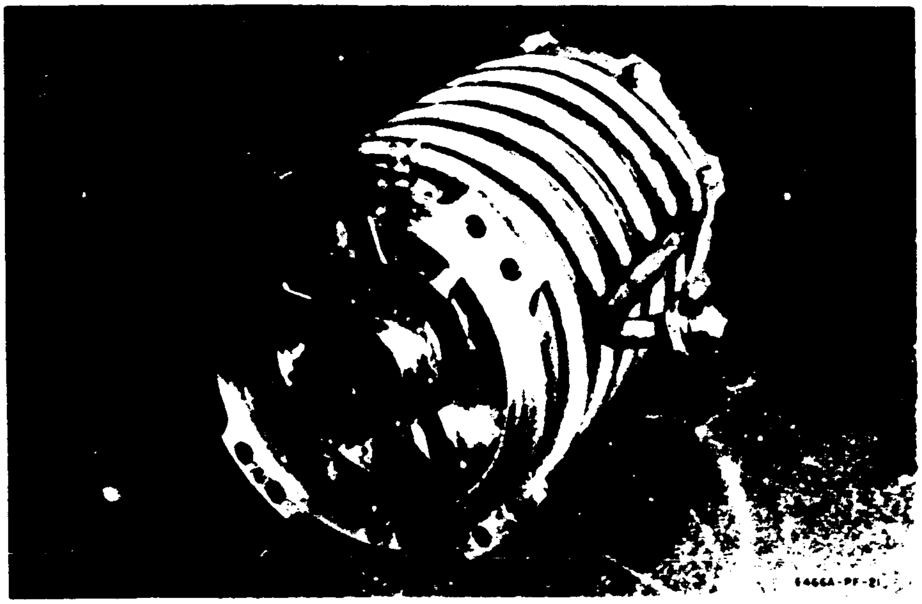

Figure 2-19. Sealed Motor, End View

The impeller which was to be used to force the oil through the system has not been satisfactory. Gas bubbles occurring in the coolant system bind the impeller which reduces the total amount of coolant circulated. While it was felt that the design of the impeller was the problem, repeated attempts to improve the design were unsuccessful. In the motors, delivered as a part of the contract, the impellers have been removed and an external coolant pump has been provided to ensure the proper flow of U-CON through the motor.

Because of the low reliability of this motor, a conventional commercial motor has been furnished for drill test purposes. Figure 2-15 shows this motor mounted to the gear box.

2.7.3 Development Recommendations

It is recommended that the concept of a liquid-cooled motor be reviewed in the continuing development program. Difficulties experienced with the liquid-cooled motor plus a cursory review have indicated that a gas-cooled motor might be more satisfactory without a prohibitive weight penalty. The problems of operating with a liquid coolant in a lunar environment indicate that a slight weight penalty might be preferable. It is further recommended that any additional weight penalty be accepted to modify the present commutator and brush design since the excessive wear with the present design is clearly unacceptable for lunar operation.

2.8 MOTOR THERMAL CONTROL

As discussed in paragraph 2.7, a circulating oil coolant fluid was selected as the motor thermal control method. This selection was made after a study and comparison of a number of potential usable systems. Table 2-2 shows the systems considered and the comparison of various pertinent parameters. As shown in table 2-2, the oil coolant system provided a considerable weight advantage. As indicated in paragraph 2.7, experience with this system has been unsatisfactory and it is recommended that the gas system be investigated for future development in the continuing program.

2.9 FRAME

2.9.1 Frame Design

The lunar drill frame has been designed to provide maximum rigidity and adequate load bearing capability within the confines of the overall drill weight limitations. Figures 1-1 and 1-2 show the frame in an erected condition.

The frame provides for four-point mounting to the side of the LEM. The mounting brackets use quick disconnect pins. When disconnected, the frame folds into a compact package for easy storage and transportation as shown in figure 2-20. The supporting members of the frame are made of 1.5-inch aluminum rods of 6061-T6 alloy and are designed to withstand 400-pound downward thrust on the drill and 4000-pound upward force. Bushings through the upper platform provide lateral support for the hoist pulley support frame.

TABLE 2-2

SYSTEM COMPARISON - MOTOR THERMAL CONTROL

	A	B	C	D
	Gas & Water	Gas	Oil & Water	Oil
Rotor Hot Spot Temp (°F)	450	450	450	450
Frame Temp (°F)	380	380	380	380
Radiator Area	1	1.01	1.05	1.17
Coolant Weight (pounds)	4.94	4.15	2.70	3.50
Coolant Temperature (°F)	330	330	330	330
Pump Required	Fan	Fan	Yes	Yes
Seals Required	Gas	Gas	Oil	Oil
Cooling System Weight (lbs)	16.26	14.85	8.72	8.3
Brush Environment	Gas	Gas	Gas	Gas
Bearing Environment	Gas/ Grease	Gas/ Grease	Oil/ Grease	Oil/ Grease
Reliability	Average	Average	Better	Better
Life	Average	Average	Longer	Longer

WEIGHT BREAKDOWN

Coolant Present In	A	B	C	D
Reservoir			0.4	0.4
Leakage	4.15	4.15	0.7	0.7
Motor Piping			0.81	0.81
Pipe to Radiator	0.4		0.4	1.59
Water Jacket	0.39		0.39	
	4.94	4.15	2.70	3.50

Hardware	A	B	C	D
Reservoir	4.15	4.15		
Pressure Reg.	0.5	0.5		
Motor Piping	1.25		0.47	0.47
Water Jacket	1.9		1.9	
Pipe to radiator	0.65	3.45	0.65	1.03
Radiator	2.66	2.7	2.8	3.1
Pump (Fan)	0.2	0.2	0.2	0.2
	11.32	10.7	6.02	4.80

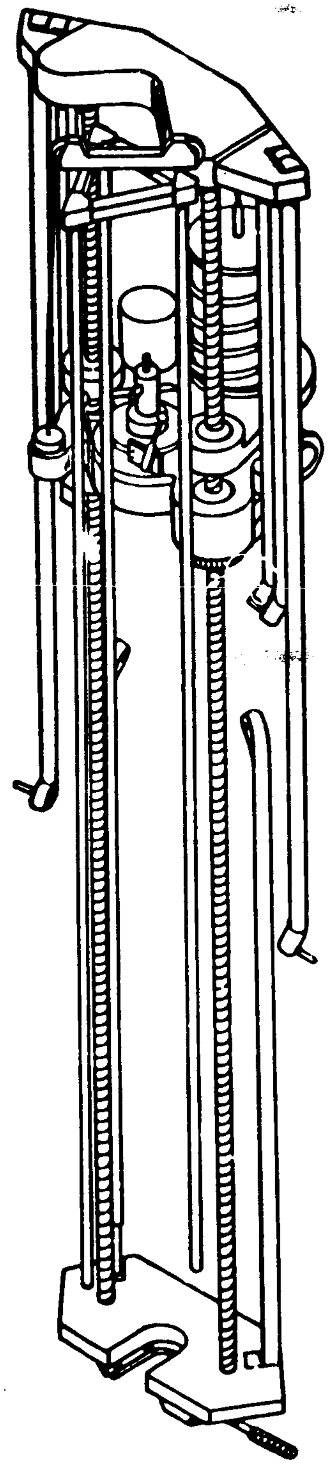

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Figure 2-20. Lunar Drill Rig, Folded for Storage

The hoist pulley support frame is used to provide the height necessary to retract the inner core barrel from the annulus of the drill string. The wire-line passes over the pulley at the top of the hoist down to the winch. As explained in paragraph 2.6, the winch is operated from the hysteresis clutch which is part of the drive mechanism. The upper and lower platform, hoist, and winch are made of 356-T6 alloy aluminum.

The ball screws are of special lightweight construction to minimize the overall system weight. The screw threads are ground on hollow steel tubes of SAE 8620 alloy. The ball nuts are part of the drive mechanism assembly shown in figure 2-15. Thrust and core breaking force is applied to the drill string through the ball screws.

The upper and lower platforms serve as attachment points for the supporting frame and as mounts for the ball screws which support the drilling mechanism. A steadying collar is attached to the top of the lower platform to prevent the core barrel from wandering or vibrating excessively when collaring a new hole. A foot clamp is attached to the bottom of the lower platform. The function of the foot clamp is to prevent the drill string from dropping down the hole while lengths of drill string are being detached during drill string retrieval.

2.9.2 Operational Experience

Laboratory experience with the drill frame, in general, has been satisfactory. Measurements have indicated that the rigidity of the system is consistent with good drilling practice. No problems of excess distortion or vibration have arisen.

Two additional braces were fastened on the bottom platform to give additional stability during early drilling tests. These braces were used for precautionary reasons only and may or may not be necessary under operational conditions.

2.9.3 Development Recommendations

Since the design of the frame shows itself to be basically sound, no development program is recommended at this time.

Further testing is also necessary to determine the stability of the system using only the four-point suspension as originally designed. If the present design proves inadequate, then a change in the design will be necessary if it is desired to retain the four-point suspension concept or two additional suspension points can be added to give a six-point suspension system. The latter approach will necessitate reevaluating the interface between the drill and AES mounting surface.

2.10 INSTRUMENTATION AND CONTROLS

2.10.1 Instrumentation and Control System Design

The purpose of the instrumentation and control system is to sense the critical drill parameters and to provide the automatic and manual controls necessary to operate and protect the drill system. Figure 2-21 is a simplified schematic showing the instrumentation which is furnished for this purpose. Figure 2-22 shows both the on-site and the remote control units. The on-site control box contains the logic circuitry necessary to control and protect the drill. The remote control is connected to the on-site control by a 100-foot cable. Either control can be used to control the drill system operation. The functions which can be controlled and/or monitored are shown on the face of the control. Bit temperature, torque, and thrust can be read quantitatively from the meters shown at the top of the panel. The desired values - i.e., values set by the operator for feed mode, feed rate, and thrust - are shown in the second row of instruments down from the top. These settings are controlled by a special keyed control handle from the three lower center controls labeled MODE, RATE, and THRUST. The feed mode controls of DOWN and UP indicate the direction in which the drill string is being driven. REAM OFF indicates no travel of the drill string in either the up or down position. Rotation in the ream mode (200 rpm) is possible in this

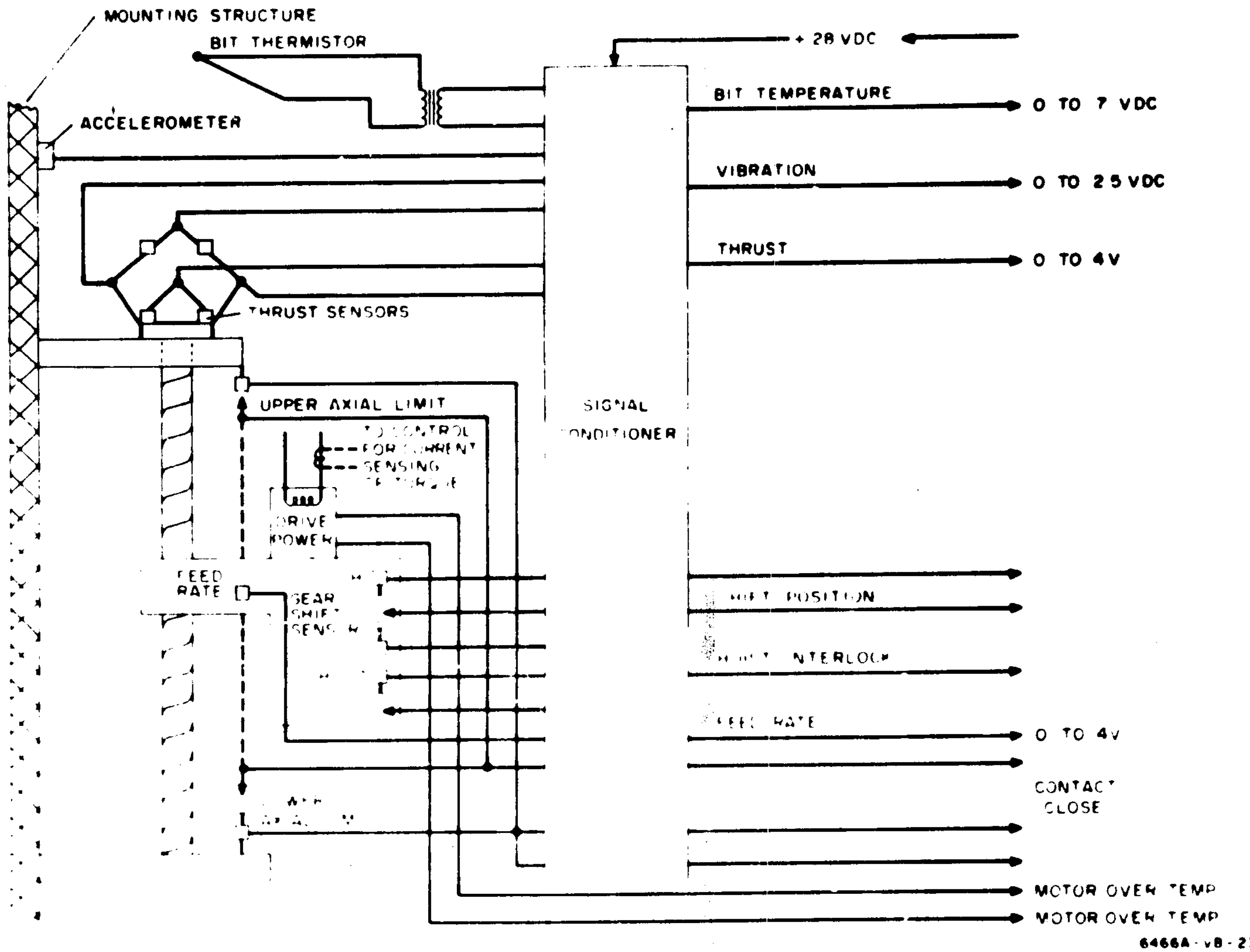

Figure 2-21. Drill Instrumentation

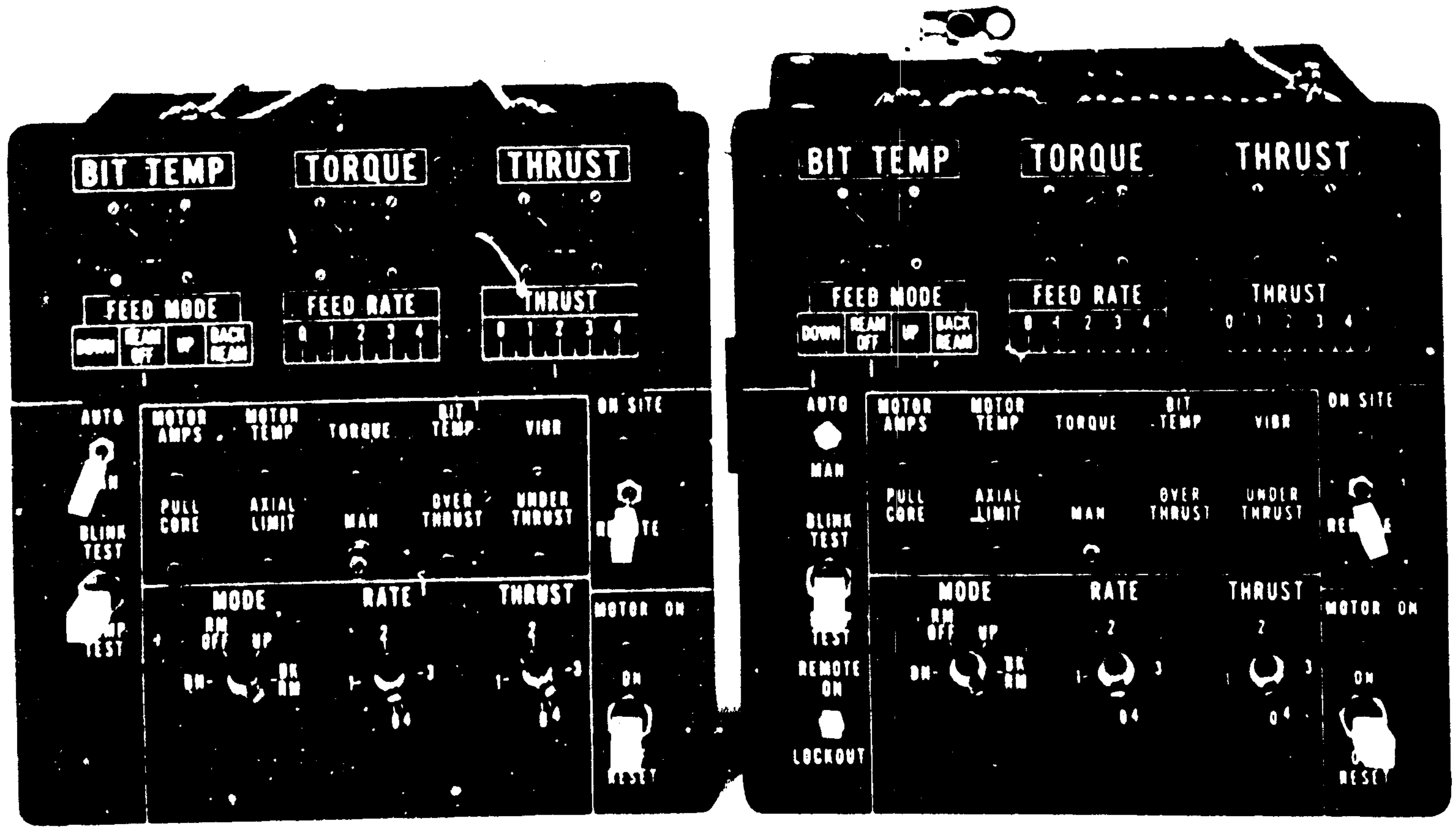

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Figure 2-22. Lunar Drill Controls

position. The back ream mod[illegible] in the low speed (200 rpm) while the drill string is being retracted. The feed rate is calibrated in inches per minute and thrust is calibrated in hundreds of pounds.

The 10 lamps shown in the center of the panel are malfunction indications with the exception of the MAN lamp which indicates manual rather than automatic operation. In automatic operation,the activation of any one of these warning lights will cause the automatic shutdown procedure to be activated. This procedure consists of stopping the feed, a 10-second delay to allow the hole to be reamed, then a shutdown of the motor. If the MOTOR AMPS or MOTOR TEMP lights are activated, the 10-second delay is eliminated. A brief discussion of each anticipated malfunction signal is given below.

a. The MOTOR AMPS signal originates in the motor starter and indicates a motor over-current condition.

b. The MOTOR TEMP signal originates from thermally activated switches in the 100-volt motor and indicates excessive temperature in this unit.

c. TORQUE is determined from the motor current and the motor characteristics. This is a gear box protection rather than a motor protection signal.

d. BIT TEMP is sensed by a thermistor in contact with the bit matrix. This signal is transmitted by wire up the drill string to the rotary joint where a rotary transformer is utilized to pass the signal to the control box. It will cause shutdown at 400°F.

e. VIBR gives an indication of excessive drill vibrations. The sensor is an accelerometer mounted on the surface upon which the drill is mounted. It is primarily a mounting surface rather than a drill protection device.

f. The PULL CORE signal is activated by a combination of thrust of 200 pounds or more and a feed rate of 1/4 in/minute or less. This indicates that the core barrel is full, a "core block" has occurred, the drill string has fractured, or that a bit has failed. These signals come from the feed rate sensor, which is a dc tachometer geared to a ball screw nut and from the thrust sensors which are strain gauges mounted on the upper arms of the drill frame.

g. The AXIAL LIMIT signal indicates that the gear box has reached its upper or lower limit of travel on the ball screws. These signals come from magnetic switches mounted on the upper platform of the drill frame.

h. OVER THRUST indicates that the thrust level is in excess of 400 pounds. This signal comes from the thrust sensors referred to in f above.

i. UNDER THRUST indicates a thrust of less than 50 pounds. This signal comes from the thrust sensors referred to in f above.

The upper switch on the right side of the on-site panel permits control of the drill to be switched to either the on-site or remote panel, and the lower switch controls the motor. The top switch on the left allows selection of automatic or manual control of the drill. The center switch on the left is a lamp test switch and the lowest switch locks out the remote control panel. This obviates the possibility of injury to personnel at the drill site by someone inadvertently activating the drill from the remote panel. The remote panel does not have this latter switch.

The gear shift sensors shown in figure 2-21 provide signals to the logic circuitry which provide lockouts so that it is impossible to rotate the drill when the gearbox is in the hoist position and to prevent down feed when in the low speed (200 rpm) gear.

2.10.2 Operational Experience

The operational experience which has been accumulated with the drill instrumentation and control system has been very satisfactory. In general, the controls are sensitive and allow the degree of protection necessary for remote operation. One exception to this general evaluation is the PULL CORE indication. It will be recalled that this light comes on and drilling is stopped when the thrust is over 200 pounds and the feed rate is less than 1/4 inch per minute. Experience has established that during drilling the feed rate apparently fluctuates markedly as the drill bit hits hard spots, as the drill frame flexes or from other undetermined reasons. Although these fluctuations are normally of short duration (fractions of a second) they are sufficient to indicate to the control system that a core block has occurred and the drilling is automatically stopped. This portion of the circuitry has been disabled in order to allow testing to proceed. A delay of a few tenths of a second should be built into the system to prevent these short duration variations in the feed rate from stopping the drill.

2.10.3 Development Recommendations

Although the presently designed instrumentation and control system is satisfactory and has worked essentially as designed, it is far from the ultimate for an automatic control system. Because of the premium placed on astronaut time on the lunar surface, a high degree of automaticity should be built into the drill. However, because of weight and reliability considerations, the feasibility of a completely automated system is open to question. It is suggested that a study be conducted to determine the degree of automaticity desirable and feasible under lunar operating conditions and that the control and protection system be redesigned in compliance with the study recommendations.

2.11 DRILL OPERATION

An Operations Manual describing the method of assembly and operation of the engineering model of the lunar drill is provided as a separate document.

2.12 HUMAN FACTORS ENGINEERING

2.12.1 Human Factors Design

Westinghouse is keenly aware of the drill/astronaut interface that must be considered in the design of any space equipment. As a result, this was a consideration in the design of the present drill and a considerable amount of task analysis was accomplished in the course of the contract. The analyses which were carried out must be considered as extremely tentative in view of the dearth of definitive information available on the drill support and transport structures and the fact that many changes will be made in the present drill concept. A comparison of table 12.2, 10th Monthly Report with table 10.1 of the Operating Instructions Manual indicates that some drilling procedures have been changed in line with design and drilling concept changes. For these reasons, the emphasis during the development phase has been on the solution of basic engineering problems rather than human factors design effort.

2.12.2 Development Recommendations

It is obvious that the present design of the lunar drill relies too strongly on astronaut participation. The weight limitation imposed by the contract forced the development in the direction of providing automation for those things that the astronaut clearly could not do and requiring many manual operations to stay within the weight allocation.

Experience with the engineering model, has indicated that basic engineering improvements must be made in the systems. Since the tradeoff values of astronaut time vs weight may change as more space experience is gained, it is suggested that any engineering improvements be made with the goal of complete automation in mind, but that emphasis be placed on solving the engineering problems in Phase II, and making final tradeoffs in the Phase III Program.

Such an approach will provide a basis for the design of a more automatic, if not fully automatic, system, which should require astronaut attention only in case of malfunction or other unusual conditions. If the problems of weight allocation can be relieved, such a system can be produced.

2.13 ACCEPTANCE TESTS

In accordance with agreements between Westinghouse and Contracting Officer's Representative, the acceptance test requirements of the contract would be considered satisfied if the following conditions were met:

a. Prime Mover Demonstration:

The prime mover subassembly to consist primarily of the motor and gear box with a dummy load generator coupled into the subassembly shall be demonstrated to be operational in a high vacuum environment. A prime mover radiator/convector unit shall be used (outside the vacuum chamber) to remove the heat generated. The motor/gearbox unit shall have a suitable connector (mechanically simulating a portion of a drill string section) between its chuck and the dummy load generator. This setup shall be mounted in the high vacuum chamber. During the demonstration, records shall be kept of chamber pressure; chamber temperature, motor input voltage, current, and power; critical spot temperatures for the entire prime mover; output rpm and torque, control functions; and the limiting and control functions. The prime mover subassembly as described shall be operated throughout a range of its functions in a cycling manner for an accumulated period of 8 hours, during which the vacuum chamber shall be maintained at it lowest possible pressure. The chamber temperature shall be ambient. The cycling manner mentioned above shall be through alternate operational intervals of 30 minutes and shutdown intervals of 15 minutes for the entire demonstration period. Throughout the demonstration, the amount of heat being removed by the prime mover radiator/convector shall be determined and recorded for reference during the field tests.

b. Rotary Seal Demonstration:

The rotary seal unit shall be set up and demonstrated according to the procedure statements of Progress Report Number 4, Section 3, and the modifying statements on procedures of Progress Report Number 8, Section 4.

c. Demonstration of - Coolant Tubes for Proof Pressure
- Drill String Couplings for Leak Check

Portions of reasonable length from two sections of drill string shall be coupled together with a standard coupling. Simultaneously (or separately if need be) each coolant tube shall be pressurized to 45 psia for an interval of 30 minutes minimum length. This demonstration is designed to both proof-pressure-check the coolant tubes and to leak-check the joint formed by the coupling. A standard helium sniffer leak detector shall be used.

d. Demonstration of Auger Flights Efficiency:

At E. J. Longyear, the demonstration of auger flight chip removal from a 15-foot section of clear plastic tubing to a simulated chip basket shall be set up as an acceptance demonstration of the auger flights' efficency. The demonstration procedure may follow that used for the earlier 9-foot test.

e. Postdemonstration Procedure

Following the above described demonstrations, any units that are also involved here may be dismantled and inspected for evidence of weak and/or damage. Minor adjustments and repairs will be permissible. After reassembly (providing any breaking down is necessary), the entire drilling subassembly shall be prepared for and used in drilling and coring a 5-foot minimum thickness of basalt (your choice). A record shall be kept of total actual drilling time plus those parameters appropriate from demonstration a. Drill bit, auger flights, core barrel, and chip basket functioning efficiencies shall be observed and recorded. The final physical condition of all parts shall be observed and recorded.

Time and funds have not allowed all of these conditions to be fully met. As indicated in previous sections of the report, component and subsystem failures during the testing period have not allowed realistic systems tests to be performed in all cases.

2.13.1 Prime Mover Demonstration

A test was set up and a preliminary run was made in the range 10^{-10} Torr vacuum chamber purchased by Westinghouse primarily for this test. The test was terminated within 15 minutes after the failure of the lubricating gears in the gearbox and the test load. This test was not completed since spare parts were not quickly available. It was questionable whether the drill motor would have survived the test since the maximum time accumulated on any motor has been 9.1 hours before failure.

Since the gearbox must have additional work done on the lubrication concept before it can be considered satisfactory, there was little expectation of its running 8 continuous hours without a failure of the dry lubricant idler gears.

2.13.2 Rotary Seal Demonstration

Westinghouse has completed this test and it is reported in paragraph 2.4 of this report.

2.13.3 Demonstration of Coolant Tubes for Proof Pressure Drill String Couplings for Leak Check

This test has been completed on all sections of drill string using the following tests procedure.

The drill rod was inserted in the master gage at the lower end and the chuck at the upper rod. O-rings were placed on the water and steam tubes as they would be in the finished rods. A special fitting was employed to apply pressure to the chuck water and steam passages. Both 40 pounds of water pressure and 40 pounds of air pressure were applied to determine passage integrity. A gaging system was used to determine any pressure drops due to leaks. No appreciable stay time was utilized. These tests were made on single rods and the combination of two rods with a simulated coupling.

The helium snifter technique was not employed.

2.13.4 Demonstration of Auger Flights Efficiency

This test has been partially successful, chips have been raised in a plastic tube for a height of 9 feet with partial success in depositing them in a chip basket. The late completion and poor quality of the 15-foot core barrel assembly did not allow the 15-foot tests to be run.

2.13.5 Drilling of Five-Foot Hole In Basalt

Because of difficulties in obtaining suitable core barrels and drill bits, this test has not been satisfactorily accomplished. Bit life times of over 10 feet have been demonstrated; chip removal to 9 feet has been shown to be feasible, but because of equipment delivery problems the quality of the core barrels and the water seal problems, the combination of drilling and chip removal to a depth of 5 feet in basalt has not been demonstrated.

2.14 LUNAR DRILL POWER REQUIREMENTS

One of the contractual requirements was an analysis of the power requirements for the lunar drill. This report was submitted as a part of the 11th monthly report.

2.15 LUNAR DRILL SYSTEM WEIGHT

2.15.1 Contract Restraint

The contract imposed a drill weight restraint of 200 pounds for the drill system excluding the power supply.

2.15.2 Delivered Lunar Drill System and Component Weights

The weights of the engineering model drill system and components are listed in table 2-3.

2.15.3 Weight Growth

The drill system growth from the proposal estimate to the predesign estimate to the final weights varied from 198-240-460 pounds respectively.

2.15.3.1 Proposal Estimate

The proposal estimate included the use of Lockalloy, a 62-percent beryllium and 32-percent aluminium alloy, as a major construction material. Properly employed this alloy would have reduced the present weights of the frame and drill string components 30 to 50 pounds. The use of Lockalloy had to be abandoned due to the intolerable delivery schedules and cost. The thermal control system for the motor (72 pounds) and the motor starter and interconnecting cables (31 pounds) were not included. The estimated weights for the other components were 10 to 20 percent under the achieved weights.

2.15.3.2 Predesign Estimates

Predesign estimates did not include the external motor coolant pump, several gearbox auxiliaries, miscellaneous items totaling 128 pounds and underestimated the drill string components by approximately 70 pounds. The latter differential was in the weights of drill rods and core barrel assemblies. The other items were within 2 to 5 percent of the achieved weights.

2.15.4 Future Weight Reduction

The use of optimum construction materials, such as Lockalloy and titanium alloys, the elimination of the external motor coolant pump, the reduction of weight of overdesigned components, and the possible deletion of components, such as the bit coolant system, found dispensable during the evaluation testing period should result in an appreciable weight reduction which would be within range of the objective. This potential weight reduction would be counteracted to a degree as the result of the possible motor development and automation studies weight penalties.

TABLE 2-3

WEIGHTS

Lunar Drill System consisting of:

Drill Frame Assembly

1 - drill frame including instrumentation		43 lb
2 - ball screws	15 lb 3 oz each	30 lb 6 oz
1 - foot clamp		2 lb 6 oz
2 - drill frame braces	1 lb 9 oz each	3 lb 2 oz
1 - lower platform bushing		1 lb 2 oz
		80 lb

Gear Box Assembly

1 - gearbox including hoist and feed rate sensor	48 lb 12 oz
1 - overshot - rotary joint holder	2.5 oz
1 - swivel joint antirotational device	1 oz
1 - chip basket clamp	6 oz
1 - overshot and cable assembly	1 lb 12.5 oz
	51 lb 2 oz

Drive Motor Assembly

1 - AED Sealed Motor - 100 Vdc	34 lb 6 oz
1 - AED Motor Coolant Pump Assembly	62 lb 14 oz
or	
1 - AMF Motor - 28 Vdc including adapter	27 lb 14 oz
1 - motor coolant radiator	4 lb 8 oz
4 - radiator fittings	1 oz
3 - flexline hoses	4 lb 14 oz
AED Motor -	106 lb 11 oz
AMF Motor -	27 lb 1[illegible] oz

Controls and Cables

1 - on-site control and protection unit	7 lb 12.5 oz
1 - remote control	3 lb 8 oz
1 - interconnecting cable (on-site - remote control)	6 lb 14 oz
1 - 100 Vdc starter	13 lb 13 oz
or	
1 - 28 Vdc starter	31 lb
1 - signal conditioner	8 lb 11.5 oz
1 - set interconnecting cables	17 lb 2 oz
1 - 28 Vdc starter - motor cables	20 lb 7 oz
w/100V starter	57 lb 13 oz
w/28V starter	78 lb 5 oz

TABLE 2-3 Continued

Drill String Assembly		
1 - swivel joint assembly		3 lb 2 oz
1 - chuck		2 lb 2.5 oz
1 - chuck-core barrel adapter		10.5 oz
20 - drill rods	2 lb 13 oz each	56 lb 4 oz
1 - upper outer core barrel assembly		11 lb 13 oz
1 - middle outer core barrel assembly		11 lb 13 oz
1 - lower outer core barrel assembly		12 lb 4.5 oz
1 - upper chip basket		3 lb 5 oz
1 - lower chip basket		2 lb 13 oz
1 - inner core barrel assembly		5 lb 13 oz
1 - bit		8.5 oz
1 - bit cooling assembly consisting of:		
1 - bit coolant radiator		19 lb 8 oz
1 - valve assembly		4 lb 12 oz
1 - flexline water hose		10 oz
1 - flexline steam hose		3 lb 1 oz
1 - air eliminator		8 oz
4 - flexline hose fittings		1 oz
4 - casing sections	1 lb 14 oz each	7 lb 8 oz
1 - casing bit		11 lb 14 oz
		148 lb 7 oz
Miscellaneous		
1 - fishing tool		13 oz
2 - Parmalee wrenches	2 lb 10 oz each	5 lb 4 oz
1 - assorted hardware	Approx.	3 lb
3 - pints of H_2O		3 lb 2 oz
1950 ml of U-CON		4 lb 4 oz
		16 lb 7 oz

System weight using AED motor - 460 lb 8 oz

System weight using AMF motor - 402 lb 3 oz

3. RECOMMENDATIONS

The foregoing text has reported on the work that has been accomplished on the lunar drill during the past year. It is obvious that if a working drill is to be developed during the next few years, effort must be initiated soon in a number of critical areas. In the opinion of Westinghouse, the areas demand immediate vigorous effort are the following:

- Diamond bit development
- Chip removal development
- Gear box development
- Drill string coupling development
- Drill motor study
- Automation techniques

The following paragraphs discuss each of these subjects in some detail and describe the scope of work which should be carried out in each area. Specific, detailed development programs are not presented herein. This information can be furnished as desired under separate cover.

3.1 DIAMOND BIT DEVELOPMENT

3.1.1 Research Program

3.1.1.1 Objective

The objective of the research program is to determine basic information concerning diamond characteristics which are germane to the diamond drilling problem and to develop a background of theoretical and experimental information which can be drawn upon during the bit development effort.

Characteristics to be examined from both theoretical and experimental approaches would include:

- Diamond cutting mechanisms.
- Diamond wear mechanisms.
- Diamond wear rates under a variety of conditions.
- Diamond temperatures under various conditons and effects of various ambient temperatures on other characteristics.
- Effect of various mechanical loads.
- Effect of orientation.
- Effect of size.
- Effect of shape.
- Effect of crystal structure.
- Effect of crystal flaws.

3.1.1.2 Approach

The research program should be initiated with a comprehensive literature survey. Visits should be made to the Bureau of Mines in Washington and Minneapolis to coordinate the Westinghouse program with that of Dr. Long in Washington and Mr. Paone in Minneapolis. If necessary, visits to South Africa and Great Britain should be made to obtain unpublished information developed by the researches sponsored by the Diamond Syndicate. The state of knowledge of diamond characteristics in various environments should be determined and this knowledge used as a basis for extension of theoretical studies or extrapolation of empirical data which can be used as a basis for experimental investigations.

The behavior of diamonds in vacuums of 10^{-10} should be a goal of this program, however, some attention should be given to the probability of diamonds actually operating in this environment while drilling on the moon. The consideration here being the possibility of lunar materials outgassing at drilling temperatures.

The experimental research program should be initiated using single diamonds of high commercial quality. These diamonds should be essentially free of flaws and sufficient numbers of "identical" stones should be initially selected for the projected experiments to minimize problems arising from variations in individual diamonds, unless the effect of such variations is to be the subject of the experiments.

Experiments should be devised to examine the diamond characteristics listed in paragraph 3.1.1.1 as well as other parameters which may prove important as a result of the theoretical or experimental program.

Experiment observation techniques should be developed to permit a maximum of first hand observation and a minimum of deduction and extrapolation.

The experimental research program should be closely coordinated with the bit development program to ensure that the data developed during the research phase is of maximum usefulness during the development program.

3.1.2 Bit Development Program

3.1.2.1 Objective

The objective of the diamond bit development program is to develop a diamond coring bit capable of drilling through at least 100 feet of basalt or granite.

3.1.2.2 Approach

The bit development program would draw heavily on the information that has been developed during the past year under NASA Contract NAS 8-20547 as well as on the results of the research program described in paragraph 3.1.1.

Bit configurations should be designed to take maximum advantage of the desirable characteristics of the various crystal structures and to minimize the influence of undesirable characteristics. Various arrangements of the diamonds in the bit should be tested to find the optimum combination of cutting ability and chip removal. This development effort would be parallel to chip removal effort described in paragraph 3.2.

Under carefully controlled and monitored conditions, a number of variables should be studied:

- Effect of loading
- Effect of diamond orientation
- Effect of bit cooling
- Effect of size and shape
- Effect of orientation
- Effect of crystal structure and crystal flaws.

As a part of the developmental program methods of measurement and observation should be developed to obtain a maximum of information from the development program. For example, the following parameters should be monitored:

- Thrust
- Torque
- Temperature at various places in the bit
- Temperature at various places in the rock
- Chip temperature
- Bit deterioration (periodic)
- Penetration and penetration rate.

In addition to the above, attempts would be made to devise methods of measuring the actual temperature of representative diamonds during the drilling process. Photographic techniques should be studied to devise a method of studying the chip removal action at the bit face during the cutting process. This development program would result in optimum configurations of diamond bits for dry drilling applications.

3.1.3 Bit Manufacturing Program

3.1.3.1 Objective

The objective of the bit manufacturing program would be to develop one or more suppliers to the point that they are capable of delivering high quality diamond bits to a rigid specification. Such a capability is necessary for the test program as well as for the follow-on production phases of the drill program.

3.1.3.2 Approach

During the bit development program, it would be necessary to utilize the services of commercial bit manufacturers to fabricate set diamond bits. These would be bits utilizing a tungsten carbide matrix in which the individual diamonds are set. In accordance with the results of the research program and the experience already gained on the existing contract, specifications would be drawn up for the manufacture of experimental bits. These specifications would carefully delineate bit sizes, tolerances, protrusion of all diamonds, and the allowable tolerances.

It would be necessary to work closely with the supplier to determine the tolerance that can be held with present bit fabrication methods, and if necessary assist the supplier in devising new methods of fabrication and quality control to meet the requirements of the specification. A comprehensive test program would be necessary to determine the tolerances that will be allowable in various areas of the bit in order to determine the degree of quality control that will be necessary.

This program would be closely coordinated with the bit development program described in the preceding paragraphs.

3.2 CHIP REMOVAL STUDY AND DEVELOPMENT PROGRAM

3.2.1 General

Chip removal has been found to be an extremely important factor in the accomplishment of successful dry drilling. It is necessary that the chips be promptly removed from the hole not only to avoid mechanical binding by the chips themselves but to remove the heat which is contained in the chips. Experience has shown that if the chips do not move quickly up the hole, high temperature in the region of the lower core barrel results in expansion of the drill which in turn aggravates the situation by causing friction against the side of the hole. This situation escalates over a period of a few seconds until the drill expands to the point that it grabs the side of the hole. The problem of chip removal is two-fold: it is partly a matter of bit design to move the chips to the outside of the hole and partly a matter of the design of a mechanism to lift the chips out of the hole.

3.2.2 Objective

The objective of the chip removal program is to devise a system which is capable of removing chips expeditiously from the immediate region of the bit, transporting the chips up the core barrel, and depositing them in a chip basket.

As discussed in the previous section, the moving of the chips to the outside of the hole where they may be picked up by an auger flight is a problem of bit design and will be covered under the bit development program.

3.2.3 Approach

A theoretical and experimental program should be established on a parallel basis to study the problem of chip removal. The theoretical program would establish an understanding of the mechanism involved and the experimental program would serve to verify theoretical conclusions and provide additional inputs to theory.

3.2.3.1 Theoretical Program

It is necessary to develop a mathematical model which will describe the motion of the chips from the time they clear the bit face to the time that they are deposited into the chip basket. This model should consider and allow the variation of such parameters as:

- Gravity
- Mass
- Particle size
- Density of the ambient gas
- Drill penetration angle
- Auger flight angle
- Drill rotation speed
- Clearance between the hole and the auger flight
- Auger flight width

The model should then be used to optimize the system design features to optimize the chip removal capability of the drill.

One additional problem that must be theoretically investigated is that of placing the chips in the chip basket. Since the centrifugal force and the lift furnished by the auger flights gives a resultant velocity vector which is upward and outward, it is necessary to reverse the direction of this vector to turn the chips in toward the center of the core barrel and allow them to fall to the bottom of the chip basket. Under lunar gravity conditions some jamming of chips at the chip basket opening may occur, and under any conditions proper reversal of the velocity due to centrifugal force may be difficult. The theoretical study should recommend techniques for accomplishing this design.

3.2.3.2 Experimental Program

The experimental program for the development of chip removal techniques would be closely coordinated with the bit development program, since the design of the bit face and proper operation of the bit is intimately associated with the ability to remove chips.

Experimental techniques should be devised to:

- Lift chips 15 feet and deposit them in a chip basket
- Monitor the movement of the chips by visual or other means
- Evaluate the efficiency of the system to deposit chips in a chip basket
- Verify the results of the theoretical program with regard to variations in drill system parameters
- Provide means of visually monitoring and photographically recording the performance of the chip removal system.

While it is highly desirable to develop a chip removal system that will permit a drill to be designed for operation without coolant, alternate designs should be considered which would incorporate a cooling system. As in other design considerations, the design of the bit should be closely coordinated with the chip removal system design.

3.3 GEAR BOX DEVELOPMENT PROGRAM

3.3.1 Objective

The objective of the gear box development program is to ensure the production of a gear box that will operate for extended periods of time in a vacuum of 10^{-10} Torr and under temperature variations ranging from -250°F to +250°F.

3.3.2 General

The gear box delivered with the engineering model of the drill has not been subjected to the low vacuum or extreme temperature variations to be expected on the moon. It is believed that by using the solid lubricant techniques operation in vacuum would be possible - the limiting factor would be the lifetime of the solid lubricant components. However, the extreme temperatures present problems which were not seriously attacked during the initial phase of the program. The present gear box is designed to operate over a temperature range of -40°F to +160°F. No development effort was expended to ensure operation outside these temperature limits.

3.3.3 Approach

Initial effort should be expended in a study program which will examine the problem areas that have become apparent in the course of the present contract. Specific areas to be investigated would include:

a. Materials - The present design would be reviewed to assess the compatibility of the materials used under extreme temperatures and to explore the possible use of other materials.

b. Temperature Control - Methods of controlling the temperature of the gear box would be investigated and estimates developed for weight and power of alternate techniques.

c. Lubrication - Lubrication techniques would be examined to determine the advisability of further development of solid lubricants for drill system applications as well as evaluation of alternate lubrication methods such as synthetic fiber gears, lubricant reserviors etc. Weight and reliability penalties for alternate approaches would be evaluated.

d. Various conceptual designs using combinations of a, b, and c above would be evaluated and appropriate tradeoffs of weight, volume, reliability, etc,accomplished. These conceptual designs would be fully analyzed to ensure proper operation under lunar conditions.

A development program should be carried out in parallel with an in support of the study program. Tests of various materials, lubrication techniques, and temperature control techniques, should be tested under the extreme environmental conditions anticipated for the operational gear box.

The functions of the present gear box would be reevaluated in the light of the experience already obtained and the current appraisal of the operational drill requirements. Changes and/or improvements in the present design would be made to take advantage of this past experience and tests of the new gear box configurations would be carried out as necessary to establish their validity.

3.4 DRILL STRING COUPLING DEVELOPMENT PROGRAM

3.4.1 Objective

The objective of the drill string coupling development is to design drill string couplings which will permit a quick, simple connection of the drill string elements while providing a reliable seal of the bit cooling passages and a reliable mating of the bit temperature sensing circuitry contacts.

3.4.2 General

In view of the space suit limitations imposed upon the type and degree of effort which the astronaut can apply, and the time and difficulties presently involved in obtaining an adequate coolant seal and contact mating, it is evident that the drill string couplings must be improved. The bit to core barrel, core barrel to core barrel, core barrel to drill rods, etc couplings require the use of supplementary gaskets to assure the coolant seal. Failure of the gasket to seal may short out the electrical leads or leak the coolant to the exterior of the drill string. The external leakage, in earth ambients, could cause a chip binding situation or the loss of a critical amount of coolant. In lunar environments, the coolant loss could seriously limit the mission.

3.4.3 Approach

Prior to a study program which will examine the problem areas which have become apparent, the following efforts should be expended.

a. A study should be made, closely coordinated with the diamond bit development and the chip removal study and development programs, to determine the possibility of drilling utilizing bits and other drill string components without coolant or a temperature sensor. During the final drill system testing, the delay in delivery of the outer core barrels and the approaching contract end date influenced the use of an experimental core barrel, which could not be sealed adequately. The results of the limited drilling without coolant, performed to test out the lunar drill and protection subsystem while utilizing bits of the deliverable bit design, indicated that there is a reasonable possibility that bit cooling and bit temperature sensing can be eliminated.

b. Should the limited data be corroborated by the above study and experiments, a study should be made to determine the simplest and most reliable mechanical coupling designs for the drill string components. These designs should take into consideration both manual and automated methods of coupling the drill string elements together and the results utilized in the Automation Study.

It should be noted here that if bit cooling and bit temperature sensing can be eliminated, the necessity of such hardware as the external radiator, hoses, valves, rotary joint, internal drill string wiring and complex core barrel and drill string channeling and joints would cease to exist. The drill system reliability, weight and size would be influenced favorably while cost, complexity and astronaut time and energy requirements would be reduced.

Should the results of the program indicated above prove negative, the following studies should be made:

a. A study should be made to provide a relatively simple sealing and coupling mechanism which would be within the work capabilities of the astronaut.

b. A study should be made, in close coordination with the Automation Study Program, to develop a simple reliable sealing and coupling mechanism for the automation design.

3.5 DRILL MOTOR STUDY PROGRAM

3.5.1 Objective

The objective of the drill motor study program is to ensure the production of a drill motor which will operate reliably during the lunar drill mission.

3.5.2 General

The dc drill motor delivered with the engineering model of the drill has not been subjected to the low vacuum or extreme temperature variations expected on the lunar surface. Testing in earth ambients has indicated that the operating time expectancy of the motor is in the order of 8 to 10 hours before failure. The sealed motor design evolved utilized a closed thermal control system employing UCON, a polyalkyline glycol, as a coolant. Design compromises made to keep weight and volume to a minimum reduced the functional capability of the internal pump and the adequacy of the commutation. It is necessary to employ an external pump, which has been provided, for coolant circulation. The UCON appears influential in reducing the life of the commutation and the brushes. The rotating seal design and the external heat exchanger appeared to be adequate. In view of the short operating time obtainable with this design, Westinghouse has provided an air-cooled motor of the same parameters and a suitable power conditioner for the drill system evaluation tests. Additional study and development will be necessary to lengthen the sealed motor lifetime for lunar applications.

3.5.3 Approach

Effort should be expended initially in a study program to analyze the problem areas which have become apparent in the course of the present contract. As a result of this analysis, the following studies should be made.

a. A study to determine if there is any practical solution to the improvement of the reliability of the present design by the improvement of the life limiting components.

b. A study should be made to determine the optimum motor concept consistent with the weight, volume, power supply, and interface dimensional restraints and consistent with an external thermal transfer subsystem which meets the weight, deployment, operational and interface restraints of the drill system.

c. An experimental model of the optimum motor should be constructed and tested to determine the validity of the study.

3.6 LUNAR DRILL AUTOMATION DEVELOPMENT PROGRAM

3.6.1 Objective

The objective of the automation development program is to design a lunar drill that provides maximum automation within the bounds of the allowable weight and volume.

3.6.2 General

In view of the current space suit problems facing NASA, it is evident that a high degree of automation is desirable in any lunar or space hardware. However, it must be recognized that automation has its costs in development time, additional weight, additional volume, and reliabilit . These factors represent dollar costs to the program and the exclusion of other experiments from the lunar payload. The decision to fully automate and accept these penalties is therefore one which should not be made lightly nor can it be made unilaterally by the lunar drill developers.

3.6.3 Approach

Sufficient experience and knowledge is at present available to allow a study of automation and automation requirements for the lunar drill. For such a study to be meaningful, mockups of proposed new hardware will be built and the present engineering model will be made available for laboratory simulation and evaluation under simulated lunar operating conditions.

The following are representative of the sequence of activities to be followed in carrying out the study and laboratory program:

a. An operation profile would be generated to determine all of the functions to be performed in the operation of the drill.

b. These functions would be described in detail.

c. Engineering design concepts would be generated to carry out these functions automatically, semiautomatically, and manually.

d. A time-line analysis would be performed to determine the time required for an astronaut to perform each of the functions. Laboratory verification of this analysis would be necessary. The time saved by automating each process would be determined.

e. Based on the above engineering design concepts, a weight analysis would be performed to determine the weight penalty for performing each function automatically.

f. Tradeoff studies of astronaut time versus weight penalty would be conducted.

g. Tradeoff studies of reliability versus additional complexity would be carried out.

h. The control function would be analyzed to determine what controls are necessary in both automatic and semiautomatic systems.

i. Additional experimentation would be carried out utilizing the model of the lunar drill to determine control settings.

j. In keeping with the general philosophy of automation developed as a result of the studies described above, additional manual or automatic controls would be incorporated into the present system as necessary.

k. Geological information is inherently available from drill information such as thrust and penetration rates, required torque, etc. Provisions would be made to read out and record such information. It is believed that the majority of such information is already available in the current control system. However, if additional sensors are necessary, they would be incorporated.

Provisions would be made for remote monitoring of all pertinent operational and scientific information. If it is desirable, such information could be relayed directly to earth laboratories.

APPENDIX A

BIT DESIGN AND CUTTING REMOVAL

A.1 INTRODUCTION

This appendix describes in chronological order the testing program conducted during the lundar drill program, in an attempt to optimize the bit design. Since the design of the bit was greatly influenced by chip removal, the bit design and chip removal are treated together.

The first three major sections deal with the feasibility of diamond core drilling in the atmosphere and in a high vacuum without an external flushing agent. The fifth and sixth sections are oriented toward a suitable bit design and the seventh and eight deal with achieving a design for making dry diamond core drilling a practical technique; that is, extending the bit life (total penetration) to a figure compatible with drilling to depths of at least 100 feet. The 8th section covers the bit testing during the Pre-Acceptance Drilling Tests and Acceptance Test.

A.2 DRY DIAMOND CORE DRILL BIT CUTTING TEST AT EARTH AMBIENT

A.2.1 Introduction

The past experience of the drilling industry has indicated that a diamond core drill bit requires the use of an added external or forced liquid or gas as a flushing and/or lubricating agent. Without this active medium the bit will heat up and destroy itself or become "stuck." The latter action is called "core blocking" and is utilized in the drilling industry as a technique for recovering core samples.

In order to understand the mechanics of diamond core drilling without an active liquid or gas, the subject test was devised. The test was set up to observe temperatures of the diamond core drill bit and the rock and the action of the drill on the rock when an active liquid or gas was not used.

A. 2. 2 Test Method

The diamond core drill test was arranged so as to drill a hole vertically in a piece of basalt rock. The basalt rock was clamped to the ceiling, and the upward drilling operation proceeded with the basalt cuttings falling free from the cutting face of the bit by the action of gravity. A vertical face of the basalt test specimen had been cut smooth with a diamond saw, and the specimen was so oriented that a test hole 12 inches deep could be drilled. The 2-1/16-in OD industrial diamond bit used for the test was started into the rock so the 1/4 in to 3/8 in of the bit diameter was extending beyond the smooth cut side of the specimen, figure A-1. Chip removal was accomplished by centrifugal force and therefore the diamonds of the bit could be observed during actual drilling as they left and then entered the kerf being cut in the specimen. The first and third holes were drilled in this fashion. The second hole was cut entirely within the basalt specimen; consequently, no part of the bit face was exposed for observation.

A. 2. 3 Test Equipment

A. 2. 3. 1 Industrial Diamond Drill

A Model 405 Longyear industrial Drill Feed Mechanism with a 2-hp electric motor was used to feed the 2-1/16-in OD industrial diamond core bit into the rock specimen. This Longyear drill has an efficient ball type feed screw with a 0.200-in pitch on the feed screw. The driving miter gear is connected to a 4-1/2-in handle turned by the operator. A two-speed, 2-hp Milwaukee motor rotated the bit at a free speed of 1000 rpm. The lower free speed of 500 rpm was not used during the test. The electric motor was rated at 12 amp, 120 volts ac.

A. 2. 3. 2 Industrial Diamond Bits

Two standard Longyear Industrial Diamond Bits were used for the test.

<u>Bit No. 1</u> Longyear Model No. BH12
Industrial Diamond Bit
2-1/16 in OD by 1-3/4-in ID by 14-in long 5/32-in kerf
Impregnated bit

BASALT (70)	Impregnated Bit	Set Bit
TEMP. OF DRILL	Below 700°F - 1600°F	450-600°F
DRILL RATE	3.66 in./min	2.25 in./min

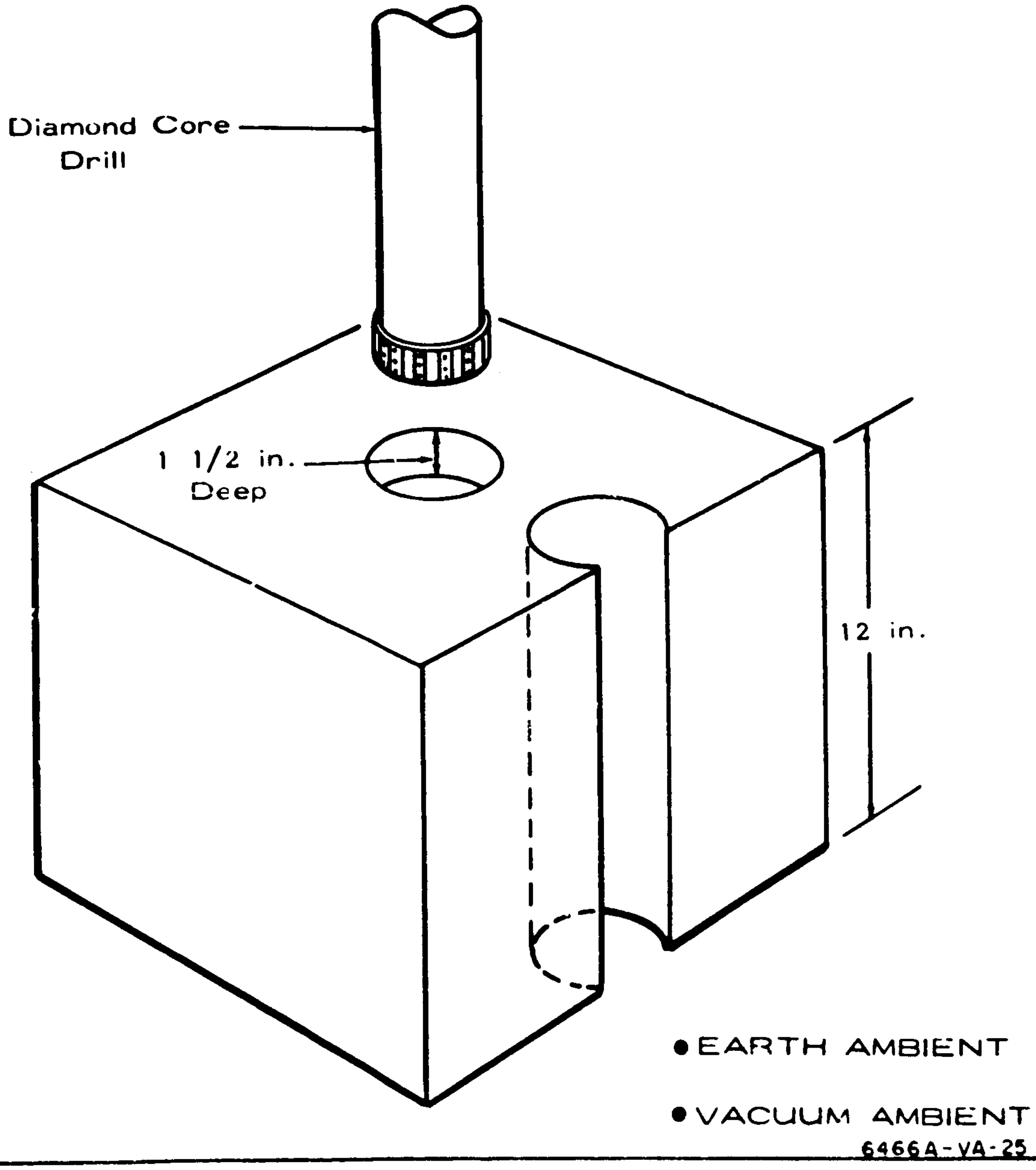


Figure A-1. Dry Diamond Core Bit Drilling Test

Bit No. 2 Longyear Model No. BH2

Industrial Diamond Bit

2-1/16-in OD by 1-3/4-in ID by 14-in long 5/32-in kerf

Surface set bit

A. 2. 3. 3 Basalt Rock Specimen

The basalt rock was obtained from the U.S. Bureau of Mines at Fort Snelling. The top and side faces had been cut smooth on a diamond saw. The approximate dimensions of the rock were 6-in x 12 in x 12 in. The rock, mined at Dresser, Wisconsin, had a Shore hardness of 79 and a compressive strength of 43,000 psi.

A. 2. 4 Test Instruments

A. 2. 4. 1 Clamp-On Ammeter

An Ampro clamp-on type of ammeter was used for measuring motor current.

A. 2. 4. 2 Photo-Tachometer

A Pioneer photo-tachometer was used to read bit rotational speed. A five-band strip was attached to the bit with drafting tape.

A. 2. 4. 3 Pyrocon Thermometer

This thermocouple type instrument was used to measure the temperature of the bit matrix at the end of each run; temperature range: 0 to 400°F.

A. 2. 4. 4 Tempilaq

The following temperature sensitive lacquers were applied to the bit to determine the maximum temperature attained by the bit.

No.	Temp	Color
1	306°F	Yellow
2	350°F	Grey
3	413°F	Lt Pink
4	475°F	White

A. 2. 4. 5 Tempilstik

The following range Tempilstik were also applied to the bit to determine the maximum bit temperatures:

No.	Temp	Color
1	500°F	Blue
2	600°F	Red
3	700°F	Orange
4	800°F	-
5	900°F	-
6	1400°F	-
7	1600°F	-

A. 2. 5 Test Procedure

The test equipment was set up as shown in the illustrations and bit no. 1 (diamond impregnated bit) was started into hole no. 1. The bit was advanced into the underside of the rock until it was cutting around the complete bit diameter.

A stop watch was used to measure the duration of the test. The operator advanced the bit into the rock by turning the feed handle at a rate which kept the drill motor operating at approximately its rated hp as indicated by the current shown on the ammeter.

A. 2. 5. 1 Test No. 1

This was a preliminary run to determine initial cutting feasibility and to check the method of taking temperatures and getting the approximate range of bit temperatures. The drilling area was darkened and drilling was continued until cuttings of a dull red color were observed at the exposed sector of the bit.

A. 2. 5. 2 Test No. 2

This test was carried out exactly as test no. 1 with the same bit and in the same hole, but the test was stopped when the dull red cuttings traveled across the entire exposed sector of the bit.

A. 2. 5. 3 Test No. 3

This test was the same as tests no. 1 and no. 2, but it was continued until the drill reached the end of its stroke (approximately 6-3/4-in hole). As would be expected of an impregnated bit, close examination showed that a few diamonds has been torn from the bit; however, the bit was still in good shape. The faster drill rate of 3.68 in per minute was partially due to the fact that near the end of the hole more of the bit was exposed.

A.2.5.4 Test No. 4

Test no. 4 was conducted using the same bit (bit no. 1) but a new hole was started. This hole was completely within the basalt rock specimen; the diamonds and matrix were not visible. Since the cuttings could not as easily be removed from the hole, a much greater torque was required to turn the bit. Evidently, the bit became damaged due to binding and overheating caused by inefficient chip removal. At about the same time, the line fuse blew and abruptly stopped the test. No time was recorded as the lights failed also. The bit was withdrawn from the hole and Tempilstik marks indicated a temperature over 1600°F. The high temperature had destroyed the cutting ability of the bit.

A.2.5.5 Test No. 5

The surface set bit (bit no. 2) was used for this test and a new hole was started (hole no. 3). The operator of the drill applied a constant 10-lb force on the feed handle. Drilling through 11-1/4 inches of basalt under these conditions caused little damage to the bit.

These tests are summarized in table A-1.

A.2.6 Conclusion

The results of this test have indicated that:

a. Most of the mechanical energy of the drilling is converted into heat in the cuttings. When a piece of paper was held to catch the cuttings, the paper charred. Even though the diamond cutting area appeared to glow red, the temperature of the drill bit did not exceed 600°F provided the cuttings

TABLE A-1

DRILL TEST DATA

Time	Hole No.	Bit No.	Distance Drilled (in)	Duration of Test (sec)	Penetration Rate (in/min)	RPM	Amp	Max Bit Temp (°F)	Remarks
2:23	1	1[1]	0.80	17.5	2.75	Test No. 1 700	---	350° (TL) 360° (P)	Cuttings Dull Red Color
2:30	1	1	2.60	57.0	2.74	Test No. 2 1000	---	413° (TL) Off Scale (P)	Cuttings Bright Red Color
2:48	1	1	6.70	109.0	3.68	Test No. 3 1000	Avg 12 Max 14	Below 700° (TS)	Some stones torn from bit
3:12	2	1	1.38	---	---	Test No. 4 450-1000	---	Over 1600° (TS)	Penetration stops - fuse blows
4:10	3	2	11.25	300.0	2.25	Test No. 5 450-1000	---	Between 450° & 600° (TL)	Bit in Good Condition

1 Bit No. 1 - 5/32-in kerf impregnated

2 Bit No. 2 - 5/32-in kerf surface set

Method of Temperature Measurement

(TL) Tempilaq
(TS) Tempilstik
(P) Pyrocon

were removed effectively. In this test, centrifugal force[1] coupled with an "open" hole provided an effective cutting removal technique.

b. If the cuttings were not removed, the heat in the cuttings overheated both the drill bit and the rock sample and caused a failure.

c. Under these "dry" drilling conditions a set bit was more effective in cutting a core sample from rock than an impregnated bit.

A. 3 DRY DIAMOND CORE DRILL BIT TEST AT HIGH VACUUM OF 10^{-9} TORR

A. 3. 1 Introduction

The previous bit tests in paragraph A. 2 indicated that an active liquid or gas was not necessary as a flushing agent, but that a mechanical technique employing centrifugal force could be used. Since the test was performed under earth ambient conditions, it is possible that the molecular film of air could have acted as a lubricant for the diamonds. The subject test was performed in a high vacuum to determine whether this molecular film of air was critical.

A. 3. 2 Test Method

Diamond bit core drilling without an active flushing or cooling medium was first conducted in air on both basalt and granite to allow comparison with drilling in vacuum. These tests were followed by outgassing tests at a pressure of 10^{-8} Torr, and finally, by a test at the maximum attainable vacuum of 5×10^{-9} Torr.

The diamond drilling test setup arranged to drill a hole vertically downward into a piece of basalt rock and a piece of charcoal granite. The rock cuttings were removed from the cutting face by centrifugal force.

In all cases, the rock specimens were oriented so that a test hole 6 inches deep could be drilled. The 2-1/16-inch OD industrial diamond bits used for the tests were started into the rock with 1/4-in to 3/8-in of the bit diameter

1. This centrifugal action has been incorporated as part of the "snow plow" auger flight cutting removal technique described in paragraph A. 5.

extending beyond the vertical face of the specimen. With the cutting face exposed in this fashion, the chips could be removed by centrifugal force and the diamonds on the surface set bits could be observed during the actual drilling.

A. 3. 3 Test Equipment

A. 3. 3. 1 Industrial Diamond Drill

A Model 405 Longyear Industrial Drill Feed Mechanism with a 4-hp electric motor was used to feed the 2-1/16-in OD industrial diamond core bit into the rock specimen. The Longyear drill has an efficient ball-type feed screw with a 0.200-in pitch on the feed screw. The feed screw is rotated by a set of miter gears. The driving motor gear is connected to a 1/2-hp electric motor. Special vacuum rated solid lubricant was applied to the gears, feed screw, and associated parts.

A. 3. 3. 2 Industrial Diamond Bit

Two identical Longyear Industrial Diamond Bits were used for the test. Bit No. 1 was used for drilling under atmosphere and during outgassing while Bit No. 2 was used for the drilling at the maximum chamber pressure of 5 x 10^{-9} Torr.

A. 3. 3. 2 Bit No's. 1 and 2

Longyear Model No. BH2 Industrial Diamond Bit 2-1/16in OD by 1-3/4-in ID by 8-9/16-in long, 5/32-in kerf Surface Set Bit

A. 3. 3. 3. Rock Specimens

A. 3. 3. 3. 1 Basalt Specimen. - This rock was obtained from the U.S. Bureau of Mines at Fort Snelling. The approximate dimensions of the rock were 8 in long by 12 in by 12 in. The rock, mined at Dresser, Wisconsin, had a Shore hardness of 79 and a compressive strength of 43,000 psi.

A. 3. 3. 3. 2 Granite Specimen. - The charcoal granite was obtained from the U.S. Bureau of Mines at Fort Snelling. The approximate dimensions were 8-in by 12-in by 12-in. The rock, mined at St. Cloud, Minnesota, had a Shore hardness of 91 and a compressive strength of 33,300 psi.

A. 3. 4 Prime Mover System

A. 3. 4. 1 Axial Thrust System

A 60 Hz, 1140 rpm, 1/2-hp induction motor with solid lubricant vacuum rated motor bearings was used in conjunction with a 242:1 ratio harmonic drive to advance the bit into the rock. The harmonic drive was plated with a solid lubricant. This combination provided a bit advancing rate of approximately 1-in/min.

A. 3. 4. 2 Drive System

A 400 Hz, 5700 rpm, 4-hp, 240/416 V induction motor with solid lubricant motor bearings was used with a 637:1 ratio single stage planetary gearbox to drive the bit. The gear teeth and bearings were plated with solid lubricant. Insulation of the motor was a high temperature, low outgassing ML type.

A. 3. 5 Test Instruments

A. 3. 5. 1 Power

Appropriate voltmeters, ammeters, and watt meters were used to monitor the operation of the 400 cps power supply and measure the input power to the motors.

A. 3. 5. 2 RPM

A strobotac was used to measure bit rotation speed during the atmosphere tests. This device could not be incorporated into the chamber for the vacuum test.

A. 3. 5. 3 Temperature

Copper-constantan thermocouples were used to monitor the temperature of the motor windings, the motor frames, and the chamber shroud temperature. Temperature readings were recorded on a 24-point thermocouple temperature recorder. The diamond drill bit temperatures were determined with the aid of temperature sensitive lacquers (Tempilaq). These lacquers ranged from 450 to 1600°F in approximately 100°F increments.

A. 3.5.4 Chamber Pressure

A Kreisman Nude gage was used to measure the vacuum. The gauge was 18 inches from the shroud and approximately 4 feet from the drill bit. It was shielded against radiation from the drill rig.

A. 3.5.5 Penetration

Scale marks on the bit and a stop watch were used to determine the penetration rate of the bit. Visual observation was possible through the chamber window while under vacuum.

A. 3.6 Test Procedure

The assembled rig and support were set up outside the vacuum chamber for preliminary running in air. At the same time, power and thermocouple feed-through connectors were installed in the vacuum chamber and checked for continuity. A pumpdown check of the vacuum chamber was then completed, with pumping continued, to ensure the cleanliness of the chamber. This pumpdown showed a rate of pumping from 73 microns to 1×10^{-6} Torr in 1 hour and 40 minutes using only the 10-in diffusion pump; a tight system was indicated. In all trials, the bit was advanced into the rock until it was cutting completely around the bit diameter. The bit was then retracted slightly by the feed motor, the drill motor was brought up to speed (920 rpm) and the bit was advanced by the feed motor upon command of the test operator.

A stop watch was used to measure the duration of the test.

A. 3.6.1 Trial No. 1

This was a preliminary run in air to obtain control data of dry diamond core drilling granite and to check the instrumentation and feasibility of the prime mover system. Bit No. 1 penetrated the granite sample to a depth of 5-1/4 in at which time, the drill motor stalled. Later examination revealed that the feed motor shaft key had dropped out of its keyway due to faulty design of the key and possible binding of the bit. This binding was attributed to poor chip removal that resulted as the drill unintentionally penetrated the last 3/4 inch with full circumference.

The drill bit temperature rose above 450°F per Tempilaq, but the upper limit could not be determined because the tempilaq rubbed off when the bit became bound.

A. 3. 6. 2 Trial No. 2

This test was carried out in the same fashion as trial no. 1 using the same bit and a basalt sample. The drill ran at 940 rpm taking a core 5-3/4 inches in length (core no. 2) with 80-percent sectio The sample cracked at a penetration of 5-3/4 inches due to faulty planes in the basalt. The bit reached a temperature between 650 and 800°F during this trial.

A. 3. 6. 3 Trial No. 3

This preliminary test was run in the same fashion as trials 1 and 2 except that the drilling was done under vacuum to check initial feasibility and to outgas the equipment. Upon installation and checkout of the system in the vacuum chamber, the pumpdown was initiated. When the pressure reached 6×10^{-8} Torr with a shroud temperature of -290°F, drilling was initiated. Drill bit no. 1 was used in a basalt sample to cut core no. 3. Penetration continued to 1-1/4 inches, at which time, the drill motor current rapidly increased and caused a shutdown. Attempts to restart the drill motor were unsuccessful; binding in the drive gearbox was indicated. During drilling, the motor and rock outgassing has increased the chamber pressure to 3×10^{-6} Torr. It was noted that when the motor current increased over normal, the chamber pressure rose rapidly by a decade and decreased rapidly when the motor was turned off, indicating outgassing from the drill motor.

Examination of the bit revealed no damage. Its condition after drilling was identical to its condition prior to the test. Tempilaq measurements indicated a maximum temperature of less than 450°F.

Examination of the drill rig revealed that the bushings in the planetary gears had failed causing the unit to become jammed.

A. 3. 6. 4 Trial No. 4

Upon the installation of a new drive gearbox incorporating Westinghouse Research Lab's gallium-indium bushing in place of the "surf-coated" bronze which had failed during trial no. 3, this second preliminary vacuum test proceeded. As in trial no. 3, the cutting was initiated at a chamber pressure of 6×10^{-8} Torr. Bit no. 1 was again used to cut a basalt core (core no. 4). During drilling, the pressure leveled off at 4×10^{-6} Torr. At a depth of 3-1/2 inches drilling was stopped and the drill motor thrust bearing, which had risen to a temperature of 120°F, was allowed to cool. When the chamber pressure reached 1.7×10^{-8} Torr with a shroud temperature of -285°F, drilling again proceeded. Drilling continued for 2.5 minutes, at which time, the maximum programmed depth of 6 inches was reached.

Examination of the bit revealed a maximum temperature of less than 450°F and no visible damage. The penetration rate was as programmed - approximately 1 inch per minute.

A. 3. 6. 5 Trial No. 5

With the successful completion of the ambient atmospheric tests (trials 1 and 2) and the preliminary vacuum outgassing tests (trials 3 and 4) the chamber was prepared for high vacuum operation. The shroud was sealed tight and readied for full LN_2 pumping. The test setup and basic procedure were the same as for trials 3 and 4 with cutting proceeding in 1-inch increments. Bit no. 2 was used to cut a core (core no. 5) in a basalt sample. The hole was started 1/16 inch deep to assure proper centering. The drill was then retracted for checking and started. The hole was "collared" to 1/4 inch deep and the bit checked for centering to reduce the possibility of side thrust. The bit was then retracted to 1/16 inch clear of the rock face. To keep the motors and gear boxes warm while the shroud was being cooled for high operation, two 12-inch long 1000-watt IR quartz tubes were installed on the rig.

After a 12-hour pumpdown, the chamber pressure was at 8.4 x 10^{-8} Torr. The motors were then checked for starting and allowed to run approximately 2 minutes. With both motors running, the pressure rose to 1.2 x 10^{-7} Torr and then decreased immediately when the motors were stopped. At 10:35 a.m. on 22 September 1965, the chamber pressure leveled off at 6.2 x 10^{-9} Torr. The drill motor was started and the pressure rose to 2 x 10^{-8} Torr. With both motors running, the pressure rose to 1 x 10^{-7} Torr and finally leveled at 3.8 x 10^{-7} Torr while drilling 3/4 inch (to 1 inch total depth). The drill was then stopped and retracted from the hole. When the chamber pressure reached 1.2 x 10^{-8} Torr at 10:41, cutting was again started. The pressure rose to 3.7 x 10^{-7} Torr and held during 1-1/4 inches of penetration (total depth 2-1/4 inches).

At 1.1 x 10^{-8} Torr drilling again commenced. The pressure held at 3.6 x 10^{-7} Torr while cutting 1-3/8 inches (to total depth of 3-5/8 inches). When cutting was stopped at 10:51:20, the pressure had increased to 4 x 10^{-6} Torr. Within 1 minute after motors were turned off, however, the pressure had dropped to 2.5 x 10^{-8} Torr.

At 11:18 the chamber pressure had reached a maximum vacuum of 5 x 10^{-9} Torr. Cutting was started and it was decided to cut to the maximum depth of 5-3/4 inches on this run. The pressure stabilized at 3.8 x 10^{-7} Torr during the penetration to 5-3/4 inches. The drill rig was then shut down and the chamber prepared for re-opening. Examination of the drill bit upon re-opening revealed no damage to the diamonds or the mastic.

A. 3.7 Summary and Conclusion

The cutting of a basalt and granite core sample at a high vacuum was accomplished by using a 2-1/16-in. diameter industrial diamond drill bit and a modified drill stand supplied by the E. J. Longyear Co., together with driving and advancing mechanisms and motors furnished by Westinghouse. These were provided with specially treated bearings and solid lubricants and assembled at the vacuum research facility of the Pittsburgh-Des Moines

Steel Company. The equipment was first checked on blocks of granite and basalt in air.

Preliminary tests were then conducted in a vacuum environment of 10^{-8} Torr, followed by tests at pressures in the 10^{-9} Torr region. Although a goal of testing in the 10^{-10} Torr pressure range was desired, the high outgassing rate of motors, drive components and rock prevented reaching and holding this degree of vacuum. During time, the vacuum was in the range of 10^{-7} to 10^{-6} Torr.

The chamber pressure was measured by a Nude gage 18 inches from the shroud and placed approximately 4 feet from the drill bit. It was shielded against radiation from the drill mechanism. The pressures measured, therefore, are not truly representative of those the bit itself saw.

In each of the tests, drilling was performed along an edge of the rock sample, allowing approximately 20 percent of the bit circumference to be exposed. This arranrement permitted the chips to escape from the cutting face and subsequently prevented binding of the standard industrial bit which was not designed for dry chip removal.

The drill bit temperatures were obtained by observing the effect on Tempilaq compounds applied to the circumference of the bit. The maximum temperature indicated during the vacuum tests was less than 450°F. During cutting in air, temperatures between 650°F and 800°F were observed.

Measurement of granite core no. 1, cut in air, indicated a bit expansion due to a temperature change of approximately 540°F.

At the conclusion of the tests, both drill bit appeared unaffected except for the loss of a few diamonds from bit no. 1, most of which had occurred during the binding period at the end of trial no. 1 where an unintentional full cutting kerf did not allow escape of the rock chips.

Drill bit speeds were between 900 and 940 rpm. However, some amibiguity existed in readings of input power. For this reason, credible information was not obtained which could be related to torque or thrust.

Penetration rates were approximately the same as in air, and generally were in accordance with the calculated rate of slightly less than 1 inch/minute, considering possible errors in timing. The fluctuations in the following table of recorded penetration rates indicate an inconsistency in the timing and also play in the feed screw rather than effects on penetration due to vacuum.

PENETRATION RATES - (in/min)

Note: Bracketed numbers indicate respective cores.

Test Conditions	Granite	Basalt
Air	(1) $\frac{4\text{-}3/4 \text{ in}}{5 \text{ min}} = 0.95$ Including 3/4-in full kerf	(2) $\frac{5\text{-}3/4 \text{ in}}{5\text{-}1/2 \text{ min}} = 1.04$
Vacuum, (10^{-8} start,)	(3) $\frac{1\text{-}1/4 \text{ in}}{2.4} = 0.52$?	
(10^{-7} during cut)	(4) $\frac{3\text{-}1/2 \text{ in}}{3\text{-}1/2} = 1.0$	
	(4) $\frac{2\text{-}1/2 \text{ in}}{2\text{-}1/2} = 1.0$	
Vacuum, (5×10^{-9} Torr start,) ($10^{-8} \times 10^{-7}$ during cut)		(5) $\frac{3/4 \text{ in}}{1} = 0.75$
		$\frac{1\text{-}1/4 \text{ in}}{1\text{-}1/2} = 0.90$
		$\frac{1\text{-}3/8 \text{ in}}{1\text{-}1/3} = 1.03$
		$\frac{1/2 \text{ in}}{1/2} = 1.00$
		$\frac{1\text{-}5/8 \text{ in}}{2\text{-}1/0} = 0.65$
		Average = $\frac{5\text{-}1/2 \text{ in}}{68} = 0.81$
Feed motor and gear rates give a calculated penetration of 0.94 in/min		

The results of this test have indicated that when earth rock is drilled by a dry diamond core drill in a vacuum of 10^{-6} Torr[1] that the effect of an increase in the coefficient of friction was not noticeable. Should the rock on the moon not contain a gas that will be released on drilling, then the friction of the diamonds may not be a critical factor. This can be understood by the work performed by Bowden and co-workers which show that although the coefficient of friction for the diamond against diamond at 10^{-10} Torr is 0.9, it drops to 0.15 at 10^{-6} Torr. The lower value is more comparable to the coefficient at atmospheric pressure (0.05). Should early lunar exploration indicate that there will be no outgassing of lunar rock, Westinghouse would consider a controlled leak to maintain a partial vacuum of 10^{-6} Torr at the drill bit.

These tests have also demonstrated that a dry diamond core drill can cut core samples from basalt and granite under high vacuum conditions providing the cuttings were effectively removed. Temperature measurements made, indicated that with efficient chip removal, the diamonds and mastic do not reach destructive temperatures. In fact, while drilling under vacuum conditions, bit temperatures were less than 450°F - a temperature at least 200°F less than that reached during earth atmosphere drilling without a cooling or flushing medium. The temperature difference while operating in vacuum may in part be due to the cooling of the rock sample by radiation to the liquid nitrogen shroud. However, this effect would not account for a 200°F difference.

1. Although the Nude gage indicated a vacuum of 10^{-6} Torr, the vacuum at the drill bit must have been less due to the impedance of the paths for outgassing to the pumps.

A.4 FEASIBILITY OF CHIP REMOVAL WITH A DRY DIAMOND AUGER CORE DRILL AT HIGH VACUUM OF 10^{-9} TO 10^{-6}

A.4.1 Introduction

This test was performed as part of a series of tests for the lunar drill program to meet the Priority Requirements A-2 of the contract. Specifically, this test was to establish the feasibility of removing the cuttings during core drilling operations in a vacuum without the use of an external flushing medium. A previous drill test which was described in Appendix A3 and Appendix A of the third progress report was unsuccessful in establishing chip removal feasibility in a high vacuum. To achieve the objective of this test, an auger type bit design was tested and chosen (Appendix B, third progress report) and the drill rig was modified to permit a maximum axial thrust of 400 pounds to be applied to the bit.

The test was conducted at the High Vacuum Facility (see table A-2) of the Pittsburgh-Des Moines Steel Company Research Laboratory by representatives of the Westinghouse lunar drill program team.

The auger drill bits used were of a spiral, surface set design (design C) which had been tested during October and November 1966 and qualified for vacuum feasibility testing. (See Appendix A, fourth progress report and the third progress report.) A slight modification to the basic design was the addition of more OD and ID gage stones to increase the reliability of the bits (figure A-2). The drill rig was modified, as described above, to limit axial thrust while all other conditions were essentially the same as those provided in previous tests on this series. To allow group observation of the drilling action during the tests under vacuum, a closed circuit TV camera and monitor were used.

A.4.2 Test Procedure

The drill rig was assembled with the same components used in previous tests except for the following modifications:

a. Drill drive gear box had been disassembled and reconstituted with fresh lubricant.

TABLE A-2

VACUUM CHAMBER CHARACTERISTICS

The following table presents essential data of the vacuum chamber.

Working Space:

Six feet, eleven-inch diameter, by eight feet long -- inside shroud.

Shroud:

Three-zone, LN_2 cooled, optically and physically tight, separable from outer shell, forming a guard vacuum space.

Vacuum:

With shroud open 1×10^{-8} torr in five hours. Inside closed shroud 5×10^{-10} torr in ten hours or less.

Pumping Speed:

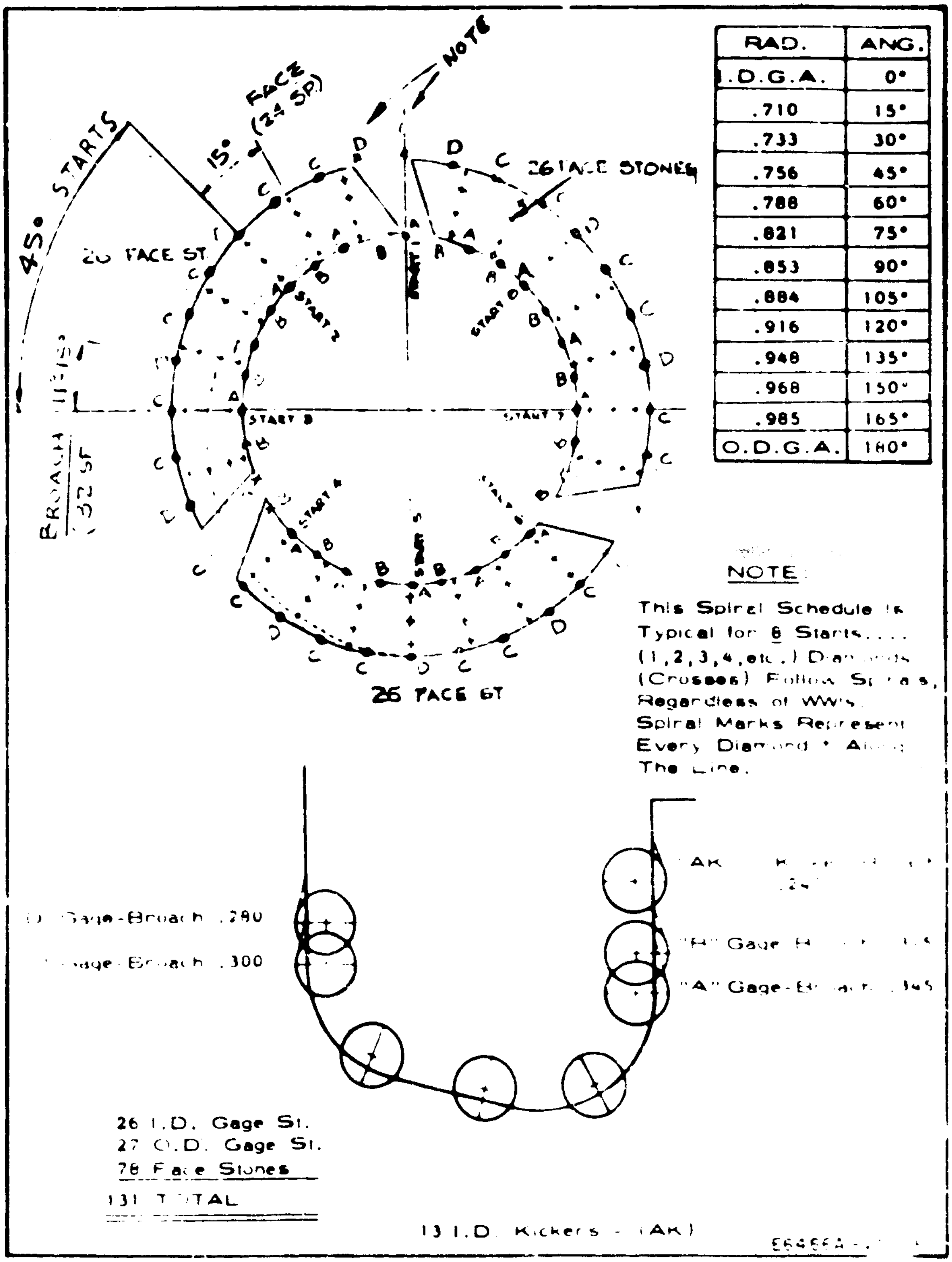
Gases condensible at 100°K - 2.6×10^{-6} torr liters/sec non-condensibles - 20,000 liters/sec.

Diffusion Pump:

Thirty-five inch NRC - rated 50,000 liters/sec LN_2 cold baffle.

Bake-out:

275°F



RAD.	ANG.
I.D.G.A.	0°
.710	15°
.733	30°
.756	45°
.788	60°
.821	75°
.853	90°
.884	105°
.916	120°
.948	135°
.968	150°
.985	165°
O.D.G.A.	180°

Figure A-2. Diamond Drill Bit SK5[illegible]

b. Advancing carriage reworked to provide means for maintaining no more than 400 pounds axial thrust, using a platform loaded with appropriate weights. See figure 1-4, third progress report.

c. An electromagnetic pickup was added to indicate rpm of the drill bit while operating in the vacuum chamber.

d. Torque and thrust measuring gauges were not used, since previous tests had provided sufficient information on these parameters.

Bit serial number U 2883 was installed with the unit on the floor of the lab. A hole was collared 1/4 inch deep in basalt, with the drill bit rotating at 940 to 920 rpm. The feed motor was operated intermittently to maintain the advancing nut free from the drill carriage, thus permitting the 400-pound weight to be the only thrust force acting on the bit.

After collaring, drilling proceeded by running for 30 seconds at a time with 90 seconds between runs for a total of 21 runs in air. A core depth of 5-3/4 inches was reached at an average rate of 0.525 inch per minute. The core was segmented in approximately 1/2-inch long pieces, each piece showing evidence of interfacial grinding. The bit appeared in good condition.

- Gear box maximum temperature was 57°C (135°F)
- Drill motor power varied between 720 and 780 watts
- Drill speed was 920 rpm.

It was noted that the adapter was slightly loose on the motor shaft causing some wobble of the drill bit, thereby contributing to the breaking of the core on either startup or retraction at some intervals.

The rig was placed in the vacuum chamber with a new basalt sample and another series of runs in air was made by operating for 30 seconds on, and 150 seconds off for 11 runs. Drilling proceeded to a 3-1/4-inch depth with the same bit as above at an average rate of 0.59 inch per minute.

- Gear box maximum temperature was 54°C (129°F)
- Drill motor power - 780 watts
- Drill bit speed varied from 918 to 912 rpm.

At this time, the setup was deemed acceptable for vacuum testing.

Bit serial number U 2881 was installed, and the basalt rock was positioned for a new hole location. The hole was collared 1 inch deep and the chamber was closed to start pumpdown. After 10 hours, the chamber pressure had reached 2.8×10^{-7} Torr, and both motors were operated for approximately 10 seconds each. Shroud temperature was at -260°F. No outgassing was observable.

At 12 hours from the start of pumpdown, the chamber pressure was at 9.2×10^{-9} Torr and the shroud temperature was at -314°F. The feed motor was started to bring the bit into the cutting position. Very slight outgassing was observed from both feed and drill motor operation before actual cutting commenced. A core of 4-1/2 inches was cut in 9 runs of 30 seconds each at intervals of 90 seconds. The average cutting rate was 1 inch per minute, with bit speed of 920 rpm. During the cutting periods, the chamber pressure rose to values between 1.0×10^{-6} and 1.6×10^{-6} Torr dropping back to values of 1.1 to 2.1×10^{-8} Torr in the 90-second periods between drillings.

Drill motor power was generally in the range of 700 to 800 watts, with one exception, when the power varied from 540 to 900 watts during the third half-minute run. Maximum gear box temperature was 20°C (68°F).

During this test, a closed circuit TV chain with image orthicon camera was employed to display the drilling action on a 17-inch monitor. The camera viewed the scene through a sighting port in the chamber and permitted excellent observation of the chip removal action. The major volume of chips appeared to be ejected in a cone of about 60 degrees included angle surrounding the shank of the drill bit, and extending upward for a distance of about 1 foot. A less dense cloud of chips was sprayed through the dust shield slot to the side of the chamber shroud and upward past the drill motor to the top of the shroud approximately 3 feet from the rock face.

Examination of the bit after this test revealed no apparent wear or damage. There was no evidence of temperature effects and no observable loss of diamonds. The recovered core was in three segments, loosely contained in the bit.

A.4.3 Summary and Conclusions

The test successfully demonstrated the capability of the selected type of diamond core drill bit to remove chips while drilling basalt in a vacuum environment without the use of an external flushing medium. The temperature of the bit apparently remained below any damaging value. No diamonds were lost, and the bit appeared in excellent condition after drilling 5-3/4 inches.

Attendees were able to watch the chip removal action on the TV monitor. A plume of cuttings was observed being ejected in a generally vertical direction from the hole. Some of the cuttings were thrown upward and adhered to the top of the cylindrical shroud (located approximately 5 feet above the rock face).

The results of this test indicate that the auger type diamond core bits designed for this demonstration are capable of efficiently removing chips while drilling in basalt rock under a high vacuum environment with no external flushing medium. It has also been shown that axial thrust must be held at a value compatible with the speed of rotation and the bit configuration.

The increased penetration rate observed while drilling under vacuum conditions may indicate better performance of the drill in vacuum than in air. This increase in performance could be caused by outgassing of the rock sample and cuttings which would aid in chip removal and bit cooling. Evidence of the amount of outgassing is given by the observed height and density of the cloud of ejected rock chips cut during the test. Another indication of increased cutting performance was evidenced by the condition of the core which had broken into three segments and showed no evidence of binding.

A.5 TEST OF THREE DIAMOND BIT DESIGNS USING AUGER FLIGHTS FOR CUTTING REMOVAL

A.5.1 Introduction

It is important to quickly remove the hot cuttings from the face of a drill bit to prevent excessive heating of the drill and also to prevent regrinding of the rock chips. Without efficient chip removal, drilling efficiency is reduced. Greater thrust is required to obtain penetration into the rock because less energy goes into actual cutting due to the energy lost in attrition of the cuttings.

Preliminary tests described in Appendix B of the second progress report indicate that auger flights on the outside diameter of a drill bit will quickly and efficiently remove the rock cuttings. These tests used a special diamond core bit having tapered auger flights (see figure A-3). The idea of using a tapered bit to distribute the axial load and subsequent cutting energy was shown to be unfeasible. This was due to an inherent weakness at the crown of the bit and a high concentration of heat buildup at that area.

The purpose of this series of tests was to determine which of three new chip removal bit designs would provide chip removal and acceptable cutting efficiency when subjected to the drill parameters specified for the lunar drill engineering model (400-lb thrust at 500 to 1000 rpm). This paragraph describes the test program the bits were subjected to, as well as the evaluation of the test data.

The bits that were tested at this time all used auger flights for chip removal. As seen in figures A-4, A-5, and A-6, the crown of each design for the subject tests was different. Bits no. 3 and 4 had a spiral, surface set design using 127 diamonds; bits no. 2 and 6 had a multi-rib surface set face using 150 diamonds; bits no. 1 and 5 had a multi-rib impregnated face using 60 diamonds on the face.

The tests were run on three different drill rigs to provide various thrust levels, rotary speeds, torques, and feed rates. The rock samples used were the same type basalt used in previous earth atmosphere and vacuum testing.

The result of these subject tests was the selection of two acceptable chip removal bit designs out of the three designs tested. These two designs are the surface set spiral and the miltirib surface set bits. However, the performance of the spiral surface set bits far exceeded the performance of the multi-rib surface set bits and, for this reason only, the spiral bits were used for later testing of chip removal bit design. Each of the spiral bits cut a total of approximately 13 inches of core before end of life. The end of life was due to wearout of the ID and OD gage stones. This wearout is believed to be caused by oxidation of the diamonds due to excessive heat. This was more noticeable when longer drilling times were used (the Tempilaq showed oxidation temperatures in excess of 700°C). The multi-rib impregnated design bits cut less than 5/8 inch of core before failure.

The subject tests were performed at the Bureau of Mines, Minneapolis, Minnesota. The help received from the personnel at the Bureau has been invaluable in performing these tests.

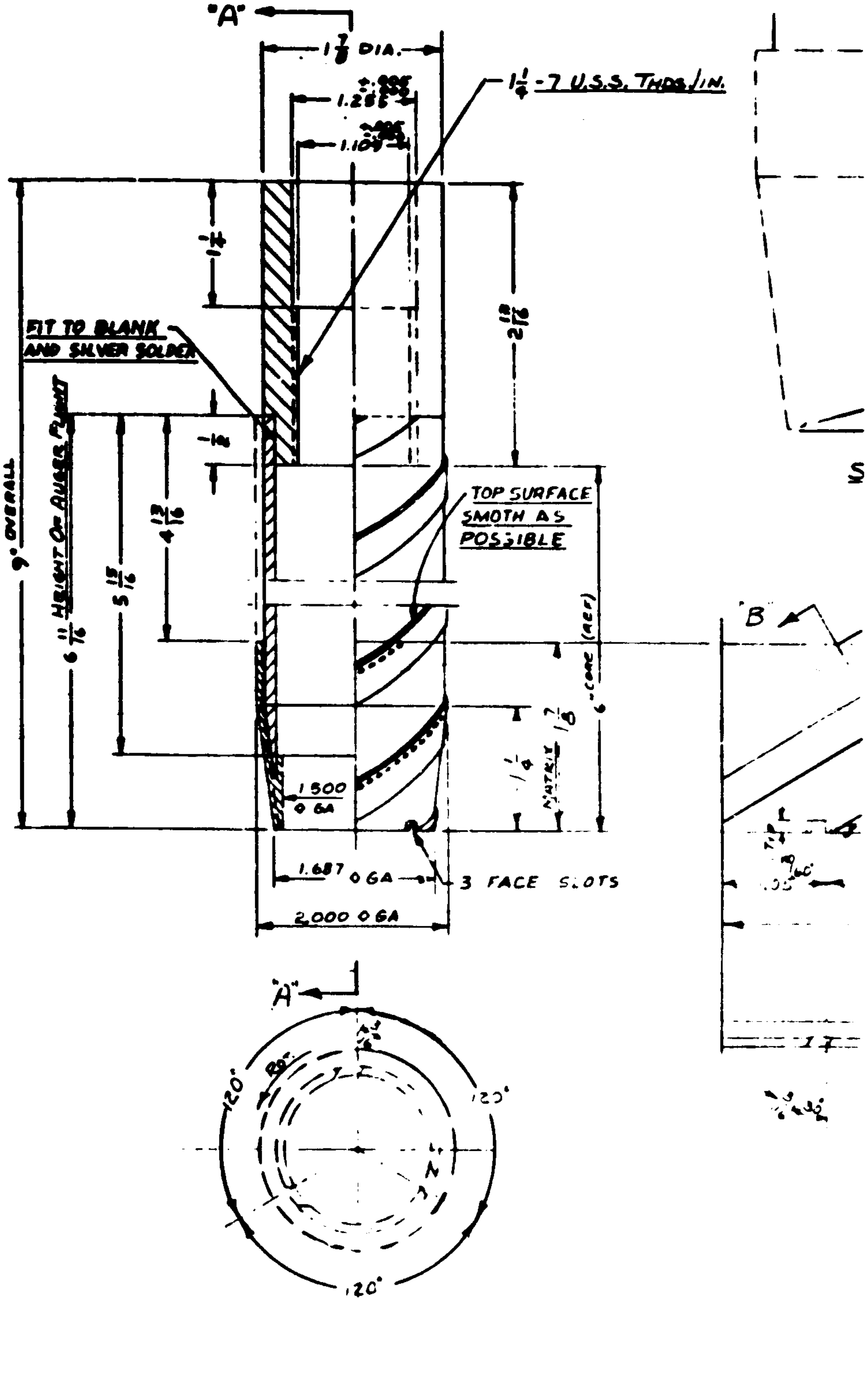
A.5.2 Test Equipment

A.5.2.1 Drills

A.5.2.1.1 Longyear Industrial Drill. - A Model 405 Longyear Industrial Drill with a 2-hp Milwaukee electric motor was used. This is the same model drill which was used for previous earth atmosphere testing (see second progress report).

A.5.2.1.2 Clipper Drill. - A Model D-30 Clipper drill with a 3-hp, 220 V single-phase electric motor was used. The 3600-rpm motor provided a rotary speed of 850 rpm at the drill bit. Advancement was by a manual feed rack-and-pinion mechanism.

A.5.2.1.3 Radial Arm Drill. - A standard Carlton Radial Arm Drill using a 5-hp, 220 V 3-phase electric motor to drive the output shaft was used. Constant thrust was maintained with an air cylinder and regulator at two available rotary speeds - 820 and 1140 rpm. Thrust could be set and held at any desired level.


"A"
$1\frac{7}{8}$ DIA.
1.255
1.109
$1\frac{1}{4}$-7 U.S.S. THDS/IN.
FIT TO BLANK AND SILVER SOLDER
9" OVERALL
$6\frac{11}{16}$ HEIGHT OF AUGER FLIGHT
$5\frac{15}{16}$
$4\frac{13}{16}$
$2\frac{13}{16}$
TOP SURFACE SMOTH AS POSSIBLE
6" CORE (REF)
$1\frac{7}{8}$
$1\frac{1}{4}$
MATRIX
1.500 O GA
1.687 O GA
3 FACE SLOTS
2.000 O GA
"A"
120°
120°
120°
B

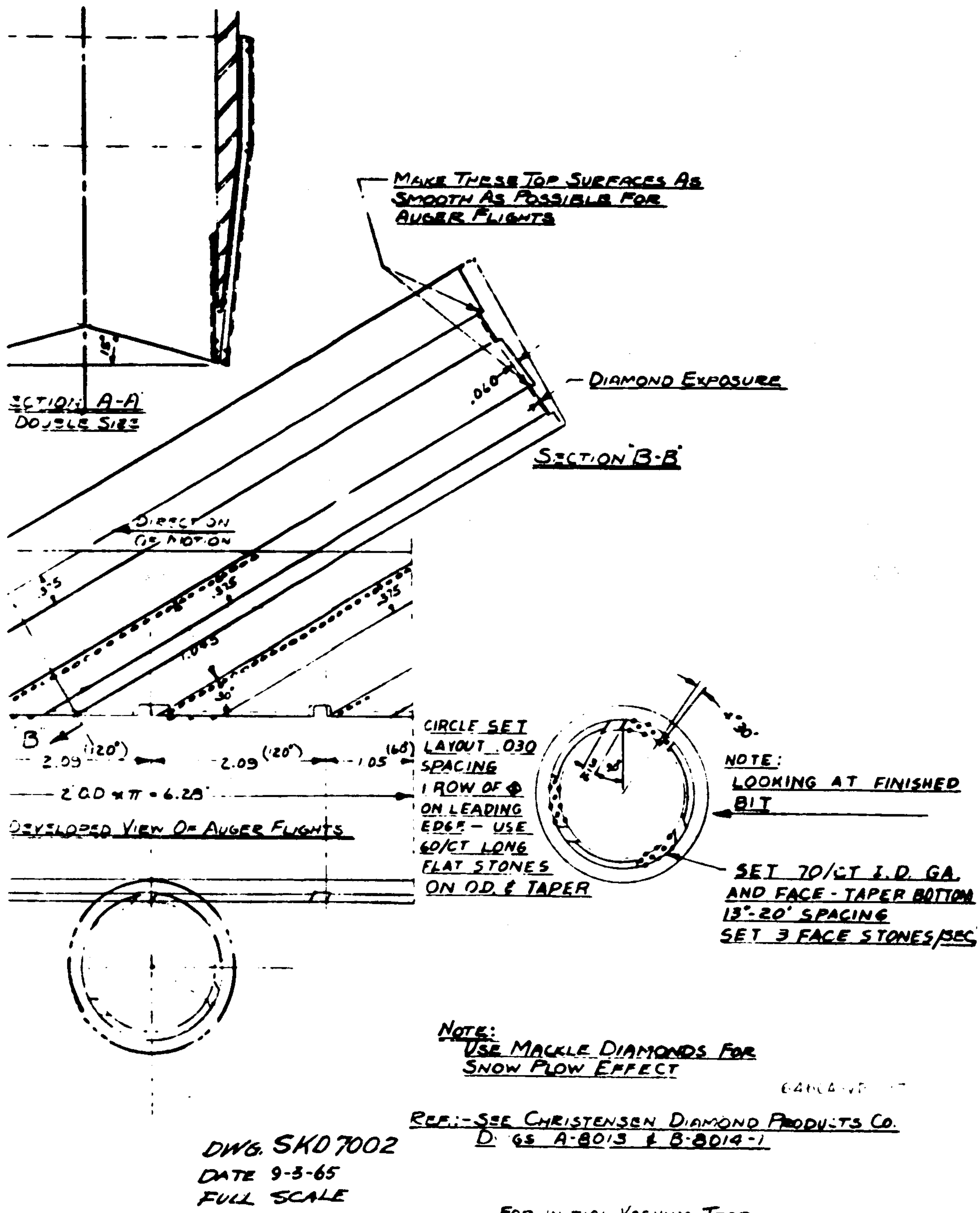


Figure A-3. Diamond Bit Tapered With Auger Flights

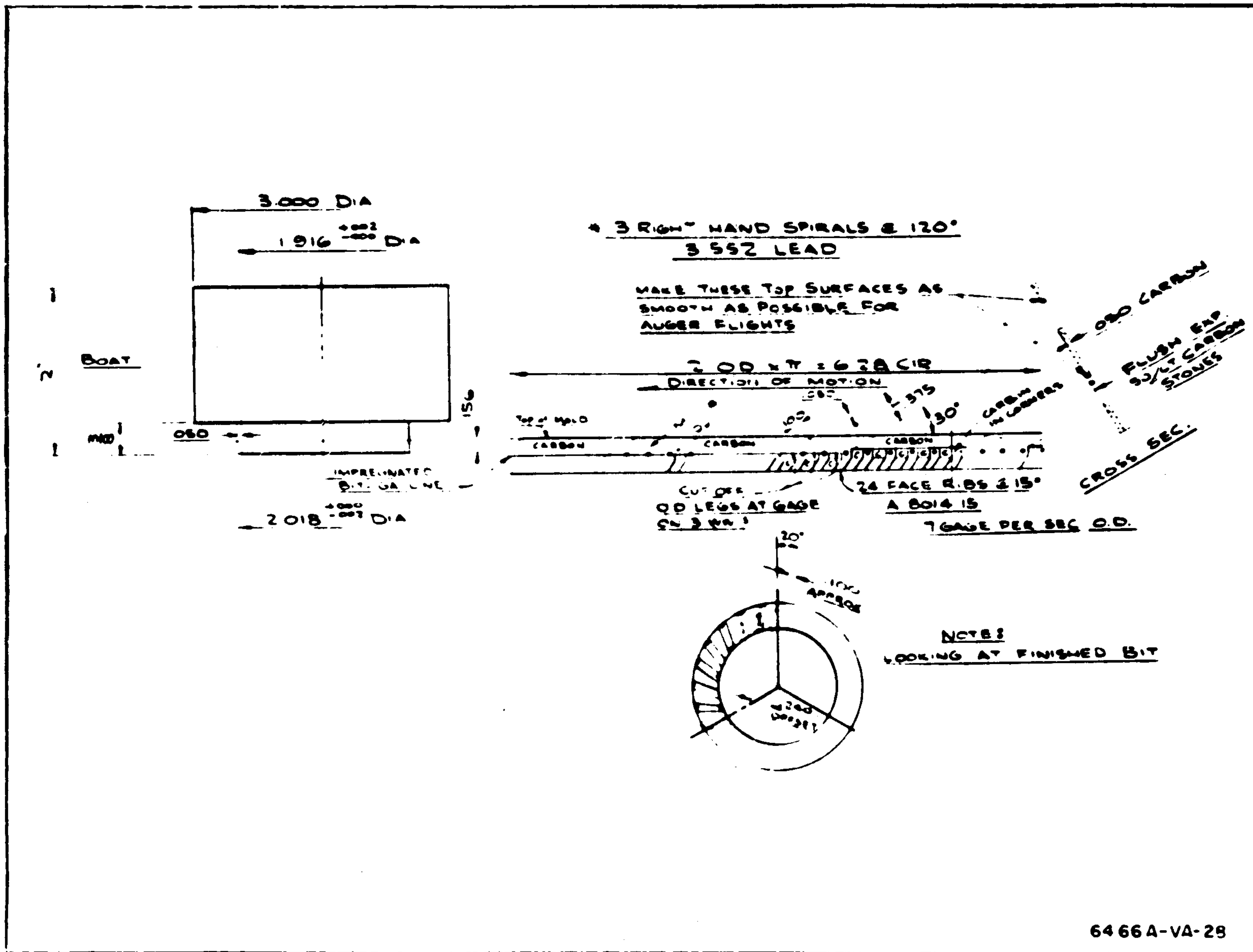


Figure A-4. Design A, Multi-Rib Imprégnated Bits No. 1 and 5

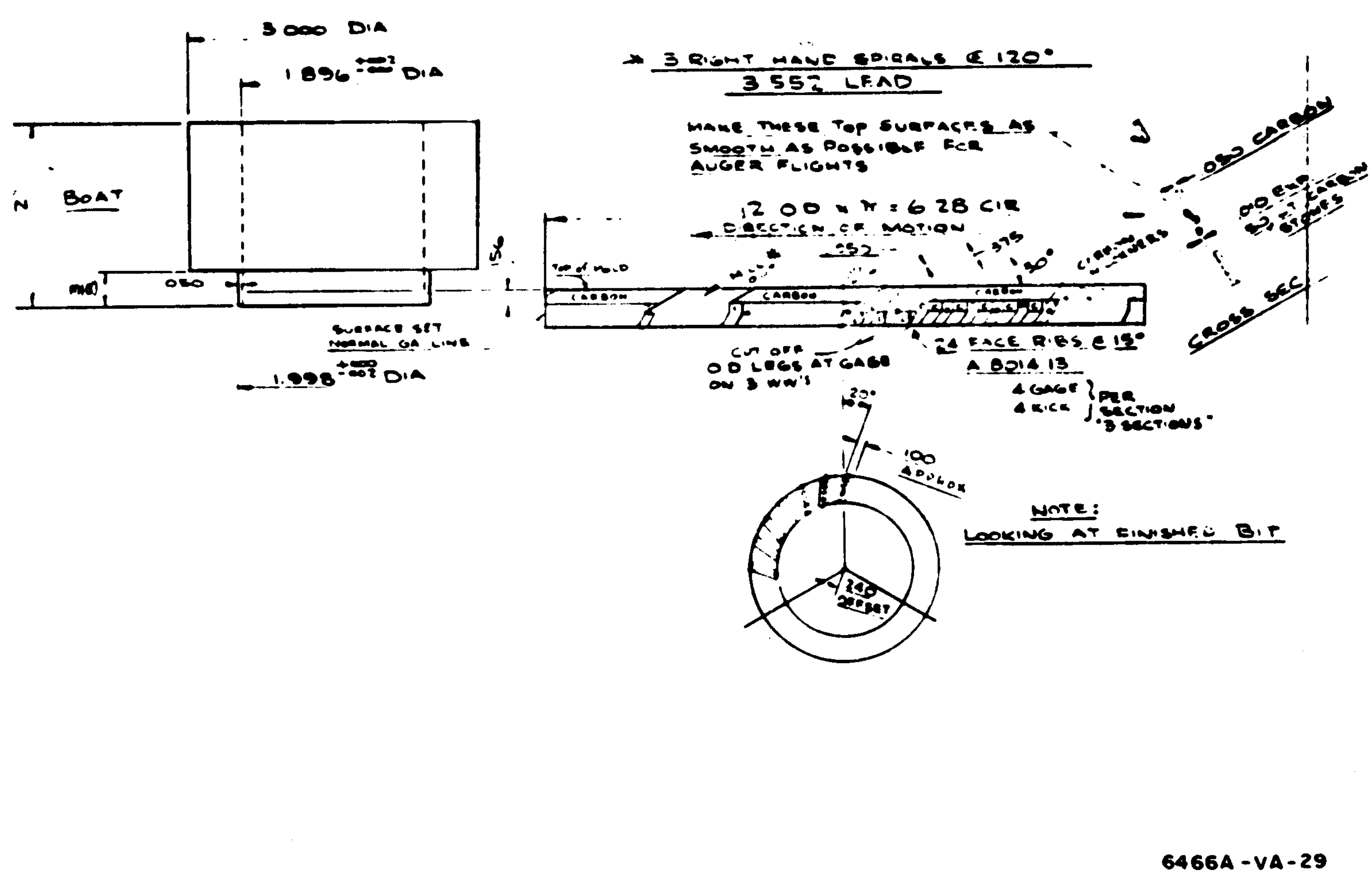


Figure A-5. Design B, Multi-Rib Surface Set Bits No. 2 and 6

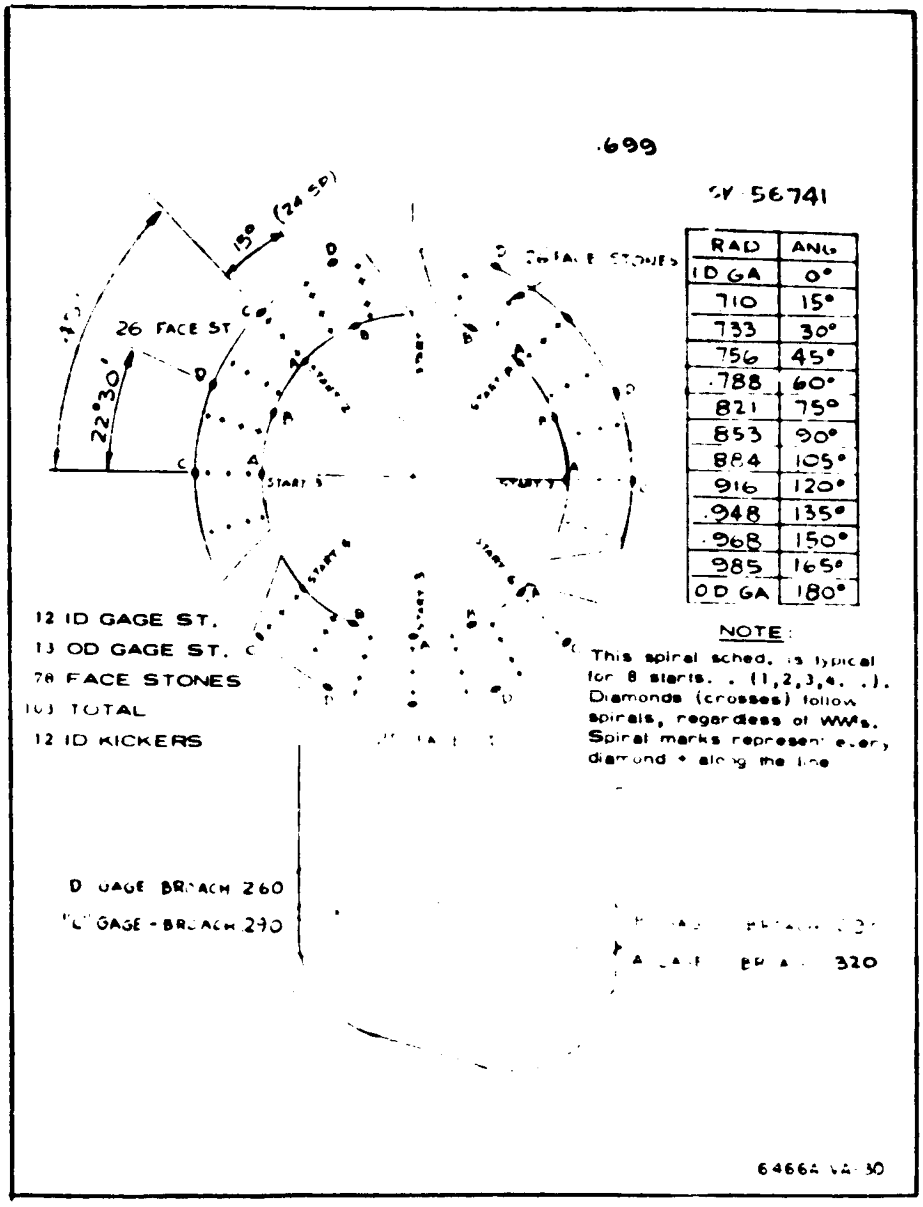


Figure A-6. Design C, Sprial Surface Set Bits No. 3 and 4

A.5.2.2 Chip Removal Bits

A total of six bits were used for tests. Two bits of each of the three designs were tested. All bits used the same auger flight design which was described and shown in Appendix B of the first progress report, also see figure A-7. Briefly, this design consists of three auger flights per bit spaced at 120 degrees and 0.060 inch wide. The flights carry the cuttings to a height of 6-11/16 inches (allowing a 6-inch core to be taken) on a 30-degree helix angle. See table A-3 for additional bit information. The bits used are shown in figure A-11.

A.5.2.2.1 Design A, Multi-Rib Impregnated Bits No. 1 and 5. - These bits shown in figure A-3 were designed with an impregnated face and hand set OD and ID kicker stones. The face consisted of 24 ribs 15 degrees apart with 60 face stones set in an extra-hard matrix. Total carat weight per bit was 4.40.

A.5.2.2.2 Design B, Multi-Rib Surface Set Bits No. 2 and 6. - These bits shown in figure A-4 were designed as was design A with a 24-rib face. However, for this design, surface set stones were used in an extra-hard matrix. The stones were offset so that there was a spiral pattern across the face of the bit. Each bit was set with 150 stones having a total carat weight per bit of 3.00.

A.5.2.2.3 Design C, Spiral Surface Set Bits No. 3 and 4. - These bits shown in figure A-4 were designed with three concentric rings of face stones which were offset to form a series of spirals from the ID to the OD of the bit face. The 127 diamonds used were set in a hard matrix and had a total carat weight of 2.15 per bit.

A.5.2.3 Rock Specimens

The basalt rock was the same as that used in previous testing which was obtained from the US Bureau of Mines at Fort Snelling. The rock was mined at Dresser, Wisconsin, had a Shore hardness of 79 and a compressive strength of 43,000 psi.

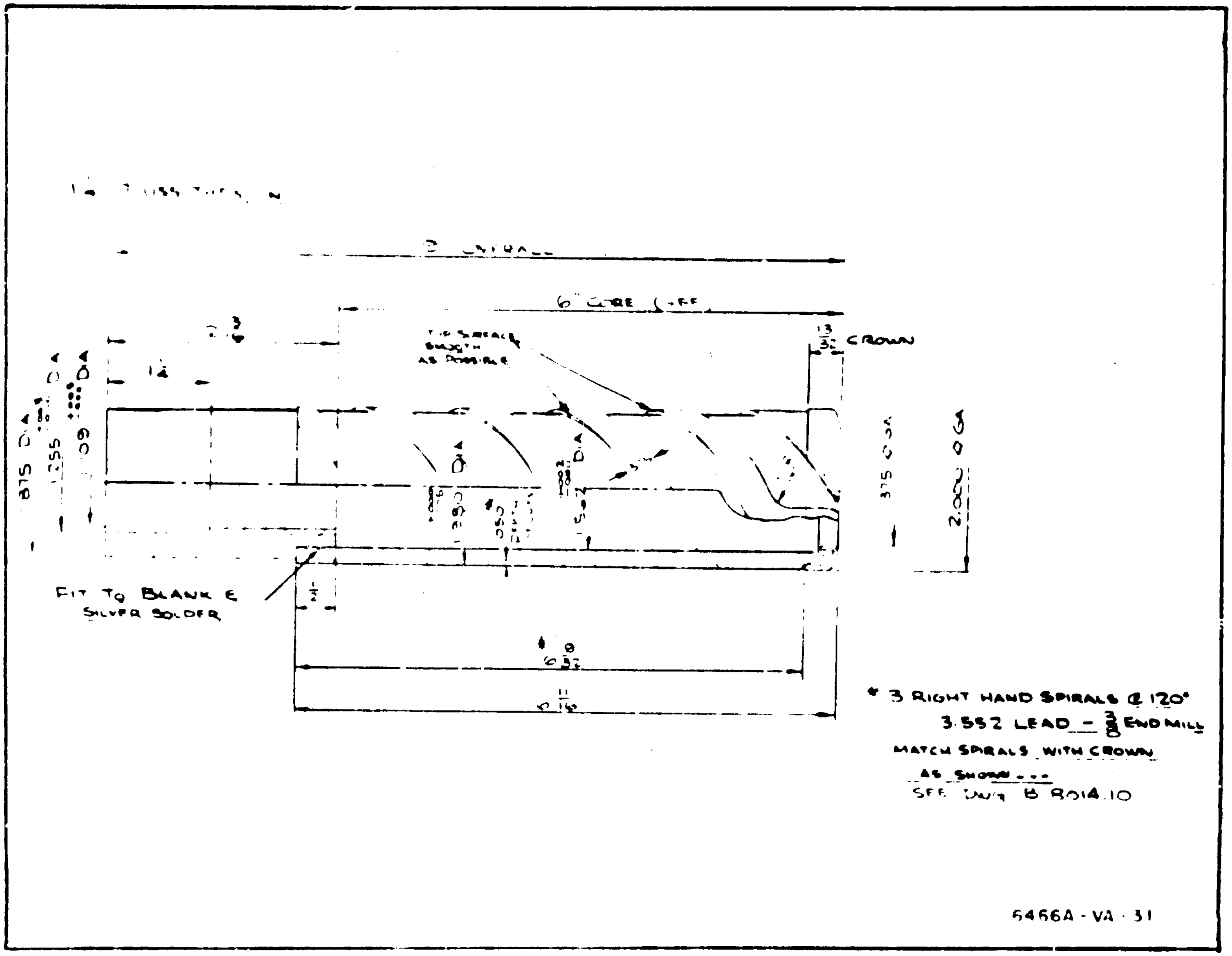


Figure A- Auger Flight Bit Design

TABLE A-3

TEST BITS USED ON TESTS CONDUCTED
October 15 - October 22, 1965

RECORD OF BITS

Item	Bit. Ser. No.	Type Sheet	Description				Plot Per Drawing	Matrix		Test Bit. No.	Bit. No.
			Type	No. Stones	Total Ct. Wt.	Size		Powder	Binder		
1	U 1164	56741	Spiral	127	2.15	50/ct	SK 56741 Fig. B-3	104	501	#4	17
2	U1155	56741	Spiral	127	2.15	50/ct	SK 56741 Fig. B-3	104	501	#3	16
3	U 1699	56754	Ribbed Surface Set	150	3.00	50/ct	B-8014.12 Fig. B-2	105	504	#2	15
4	U 1700	56754	Ribbed Surface Set	150	3.00	50/ct	B-8014.12 Fig. B-2	105	504	#6	19
5	U 1701	56755	Ribbed Imp.	60	4.40	--	B-8014.16 Fig. B-1	105-s*	504	#1	14
6	U 1702	56755	Ribbed Imp.	60	4.40	--	B-8014.16 Fig. B-1	105-s*	504	#5	18
					* 105-s On Top Of Imp.						

A.5.3 Instrumentation

A.5.3.1 Power

Input power to both the Longyear and Clipper drills was measured with a clamp-on ammeter. Power to the radial arm drill was not measured because an appropriate watt meter was not available.

A.5.3.2 RPM

Both a Strobatac and a phototachometer were used to determine the rotational speed of the drill bits.

A.5.3.3 Torque

A torque table incorporating a strain gage output was fabricated for the tests. Maximum measurable torque was approximately 15 ft-lb.

A.5.3.4 Temperature

As in previous bit tests, temperatures were measured with a Pyrocon and Tempilaq temperature sensitive lacquers. These lacquers ranged from 400 to 1000°F.

A.5.3.5 Penetration

Penetration was determined with a micrometer and an extendable scale which moved with the drill motor slide. Time was kept by the drill operator with a stop watch.

A.5.4 Test Procedure

Drilling was conducted in air on similar basalt samples using three different drill rigs (see paragraph A.5.2). During testing of the bits, it was found that both the Longyear and the Clipper drill rigs tended to vibrate and possibly damage the bit under test. Therefore, testing was completed on the Radial Arm Drill which offered more stability and flexibility of the drilling parameters.

In all cases, the drilling tests were arranged so as to drill 6-inch deep holes vertically downward into the rock samples which were appropriately oriented and clamped to the base of each rig.

The drill bits under test were "collared" to a depth of approximately 1/2 inch and drilling proceeded downward for intervals of 15 to 90 seconds. Prior to each run, thrust and rotary speed (rpm) were fixed while input power, torque, penetration rate, and temperature were measured and recorded. For the test series, the "fixed" parameters of thrust and rpm were varied through the following ranges:

Thrust	100 to 500 lbs
Rotary Speed	750 to 1140 rpm

In all runs, the test bits were oriented so as to cut a full kerf in the rock with chip removal being solely accomplished by the bit face design and the auger flights on the outside diameter (OD) of the bits.

A.5.4.1 Longyear Drill Trials

The preliminary run used bit no. 1 at a thrust of 400 pounds and an rpm of 800. Initial contact at 400-pound thrust damaged the bit and ended the test. No penetration was measured.

Other trials on the Longyear drill were made with bit no. 2, 4, and 5. Various thrust levels were used (100 to 300 pounds). Bit no. 2 penetrated well, but was hard to collar and tended to chatter during penetration. The total core length cut with this bit before failure was 5.80 inches at an average penetration rate of 0.358 inch/minute.

The multi-rib, impregnated bit (bit no. 5) was run at 118-pound thrust, 720 rpm. This bit heated up rapidly and failed after 150 seconds of running time. Penetration was 0.537 inch before failure at an average penetration rate (PR) of 0.175 inch/minute.

The first of the spiral, surface set design bits was also tested on the Longyear machine. The bit collared easily and was run for intervals of 30 to 60 seconds at thrust levels of 100 to 300 pounds for an average rpm of 758. The average penetration rate went from 0.859 inch/minute to 0.505 inch minute. No chatter was observed and the bit cut to 6 inches without any appreciable signs of wear.

A.5.4.2 Clipper Drill Trials

Because of the tendency of the 2-hp motor on the Longyear drill to load down under drilling, the next series of tests were run on the 3-hp, 850 rpm Clipper drill. Bits no. 2 and 4 were tested on this rig.

Bit no. 2 which had penetrated 5.3 inches on the Longyear machine was further tested on this drill rig to see if the previously observed chatter would be eliminated. However, the chattering was still present and the bit only penetrated another 0.50 inch at 200-pound thrust before failing.

Bit no. 4, which had previously taken a 6-inch core was then tested on the clipper drill - average penetration rates of 0.344 to 1.250 inches/minute at 820 rpm and thrusts of 200 to 400 pounds. The bit cut smoothly to a total depth (including 6-inch cut on Longyear drill) of 12.9 inches. Chip removal was excellent throughout these runs. Temperatures measured with the Pyrocon during all but the last two runs did not exceed 365°F while Tempilaq measurements indicated a matrix temperature of 500 to 700°F. The final two runs with this bit indicated that the bit had reached the end of its life for the penetration rate dropped and temperatures per Tempilaq exceeded 1000°F.

A.5.4.3 Radial Arm Drill Trials

The testing of the final two bits (bits no. 3 and 6) was done on the radial arm drill. Because of the limited time, the torque and input power were not measured during these trials. Two of the available rotary speeds (820 and 1140 rpm) were used for these tests with thrust levels set from 300 to 500 pounds.

The backup multi-rib surface set bit (bit no. 6) was first tested. Average PR ranged from 0.318 in/min at end of runs to 1.320 in/min. Observed Tempilaq temperatures rose at the bit wore, but they did not exceed 1000°F. The bit cut a total core length of 4.75 inches before it stopped cutting. An examination of the bit after testing revealed the extensive loss of ID and OD gage stones.

The last bit tested was the backup spiral, surface set bit (bit no. 3). The performance of this bit was excellent. For thrust levels of 300 to 500 pounds and rpm's of 810 and 1140, the average penetration rates varied from 0.648 in/min (last run) to 2.642 in/min. In fact, during one run at 500-pound thrust and 1140 rpm, a PR of 2.912 in/min was observed. A series of runs with this bit at 400-pound thrust and 810 rpm were made. During this time, temperatures as indicated by the Tempilaq stayed consistently between 700 and 800°F. Chip removal was excellent and the total core length cut was 12.9 inches.

A.5.5 Summary and Conclusions

The more elaborate instrumentation, provided for this series of tests, gave a more quantitative insight into the performance of chip removal designed bits while drilling in a given rock without an external flushing or cooling medium. The average penetration rates per thrust level and rpm's have been computed and plotted in table A-4 and figures A-8, A-9, and A-10.

TABLE A-4

CALCULATION OF PENETRATION RATES

Design	Bit No.	Penetration Rate	Thrust	RPM	Cumulative Depth of Cut (in)	Comment
C (spiral)	3	0.927	300	810		
		1.064	400	810		
		1.498	500	810		
		0.828	300	1140		
		1.647	400	1140		Operated on radial arm drill
		2.004	500	1140	5.84	
		0.823	400	810		
		2.642	500	1140	11.78	
		0.648	400	810		
		0.848	500	1140	12.90	
C (spiral)	4	0.505	100	758		Operated on Longyear drill
		0.552	200	758		
		0.859	300	758	6.00	
		0.613	200	817		
		1.062	300	817		

TABLE A-4 (Continued)

Design	Bit No.	Penetration Rate	Thrust	RPM	Cumulative Depth of Cut (in)	Comment
		1.250	400	817	11.70	Operated on Clipper drill
		0.334	200	817		
		0.500	300	817	12.90	
B (ribbed)	2	0.300	125	788		Operated on Longyear
		0.394	125	761		
		0.373	125	658	5.3	
		0.359	200	820	5.8	
B (ribbed)	6	0.869	300	810		Operated on radial arm
		1.320	400	810		
		0.182	300	810		
		1.215	400	810		
		0.318	300	1140		
		0.693	400	1140		
A (ribbed impreg-nated)	5	0.175	100	720		Operated on Longyear drill - would not drill
A (ribbed impreg-nated)	1	Damaged when operator did not feather the bit into the rock				

The performance of the design B bits (multi-rib, surface set) was good. At the end of each run with these bits, the hole was clean and chip removal was deemed to be satisfactory. However, the observed wear of the bit (loss of gage stones), the vibration during penetration, and the maximum core lengths cut (5.8 and 4.75 inches) are indications of a less than satisfactory design for reliably demonstrating chip removal at high vacuum.

It should be noted that the four bits of design A and B incorporated an extra-hard matrix to hold the stones. This matrix material did not noticeably increase the performance of the bits and, in fact, may have contributed to the rapid thermal rise which occurred when the design B bits were tested.

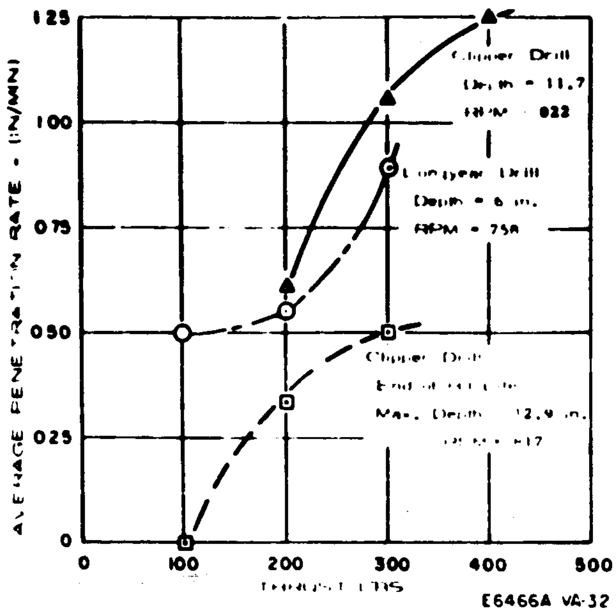


Figure A-8. Bit No. 4, Three Concentric Ring Spiral, Design C-12.9-in. Core

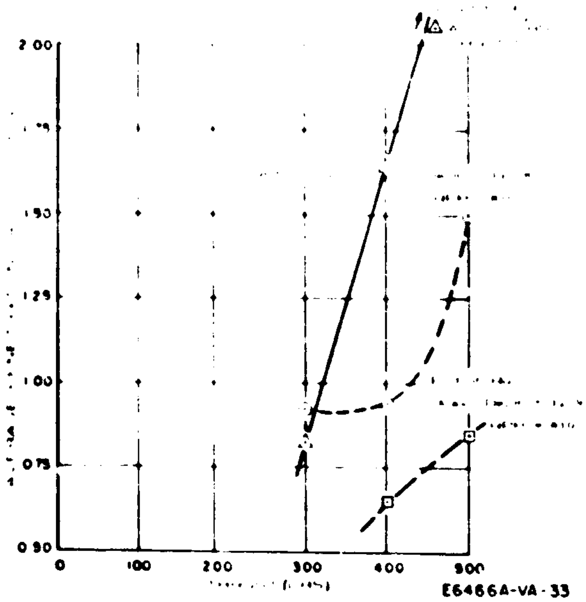


Figure A-9. Bit No. 3, Three Concentric Ring Spiral, Design C-12.9-in. Core

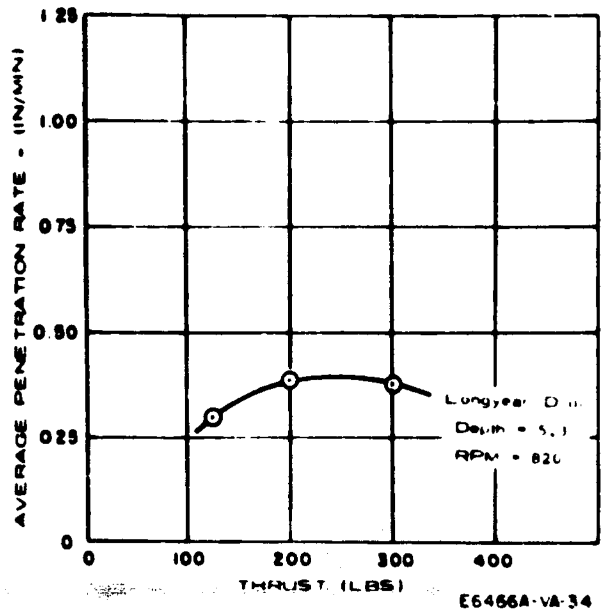


Figure A-10. Bit No. 2, Multi-Rib Surface Set, Design B
5.8-in. of Core

By far, the best performing design was the spiral, surface set (design C, bits no. 3 and 4). Both bits cut total core lengths of 12.9 inches at thrust levels of 300 to 500 pounds and at higher penetration rates. The observed loss of gage stones from the bits was gradual, and it was not until both bits had cut 12 inches of core that grinding of the core and subsequently lesser penetration rates were noted.

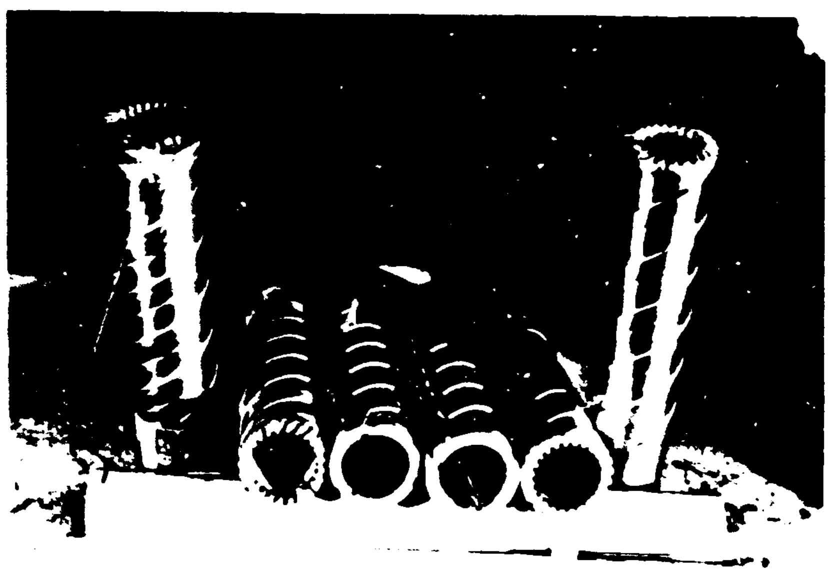


Figure A-11. Bits Using Auger Flight Design

It was noted during testing that there was a discrepancy between temperatures measured with the Pyrocon instrument and those measured with the temperature sensitive lacquers. Because of the time lag that resulted before the Pyrocon could be touched to the test bit and the difficulty in maintaining contact with the matrix, the Pyrocon measurements are grossly inaccurate. The temperature lacquers do provide accurate measurements but are only capable of giving general temperature ranges. Future R and D testing must incorporate bits instrumented with embedded thermal sensors.

These tests have demonstrated the ability of dry diamond core drills to provide efficient chip removal while cutting core in basalt specimens. The testing of three different chip removal bit designs has enabled the Lunar Drill Program Office to choose a bit design (design C). New bits of design C will be modified by the addition of additional gage stones and tested in a vacuum environment.

These tests have also enabled the lunar drill program team to obtain more definitive information on the performance of chip removal bits at different thrust levels, torques, and rotary speeds.

A.6 TESTS OF SPIRAL SURFACE SET BIT (DESIGN C)

A.6.1 Introduction

These tests were performed to obtain additional data on the auger flight chip removal bit (design C) and the modified advancing mechanism to be used for a demonstration of chip removal without an external flushing medium under vacuum conditions.

The subject tests were conducted at the E. J. Longyear Company and the Research Center of the U. S. Bureau of Mines, Minneapolis, Minnesota from 30 October to 9 November 1965, by members of the Westinghouse lunar drill program team.

As described in paragraph 1.3 of the third progress report, the drill rig was modified to limit the axial thrust while allowing a variable feed rate. The drill rig was also modified to eliminate the chattering noted in earlier tests. Prior to test number 5 of the subject tests, three 3/8-inch diameter holes were made above the crown of the bit. The purpose of these holes was to aid the removal of the cuttings which moved across the face of the bit from the ID to the outside.

A.6.2 Test Procedure

The drill rig was assembled and tests numbers 1 through 4 were run at the E. J. Longyear facility. The main purpose of these tests was to check the effect of the drill rig chattering on cutting and to make appropriate modifications to eliminate this factor. The last three tests (tests numbers 5 - 7) were conducted at the Bureau of Mines. Here, the bit design itself was modified and run on the radial arm drill used for previous tests conducted at the Bureau. Even though it was felt that the basic design of the bit was capable of demonstrating chip removal in vacuum, members of the lunar drill program team wanted to evaluate the effect of adding relief holes above the crown of the bit.

Bit serial number U 2879 was installed on the unit. To provide axial thrust, 250 pounds of weight were attached to the top of the Longyear Model 403 Drill (3-hp, 750 rpm). With the 115-pound weight of the drill itself, this provided a maximum axial thrust of 365 pounds. During these tests, the play in the rig and the bracing of the rock sample allowed excessive chattering. Reaming of the hole due to excessive play was also evident. It was noted that the degree of chattering directly influenced the penetration rate which varied from 1.18 in/min to 3.6 in/min. At the conclusion of tests numbers 1 and 2, a total of 6.42 inches of core had been taken. To damp out the chattering which was thought to be predominantly torsional vibration, it was decided to add a 30-pound flywheel to the shaft of the drill.

With the addition of a flywheel, drilling of hole number 2 was continued. During this set of tests, chattering was reduced and the penetration rate varied less (0.72 in/min to 0.52 in/min). The penetration proceeded to a depth of 3.27 inches (total core length for the bit of 9.69 inches) at which time the test was stopped.

The same bit (U 2879) was sandblasted and installed on the radial arm drill at the Bureau of Mines. A 400-pound down force was set and the drill was rotated at 1140 rpm. Drilling proceeded for 30-second intervals at a penetration rate of about 0.50 in/min. As the test data shows, the core tended to break off at the end of about 1.5 minutes of cutting. It was thought that the breaking might be caused by the cuttings at the ID of the bit not being able to escape across the face of the bit.

At this point, three 3/8-inch diameter holes were put above the crown of the bit as seen in figure A-12 to aid the removal of chips from the face of the bit. The axial pressure was set at 400 pounds with the rpm at 1140. Drilling took place for 30-second intervals. The addition of these holes did not markedly improve the penetration rate or prevent the core from breaking off at the end of each run. The penetration rate varied from 0.62 in/min to 0.42 in/min. It was concluded that the fracturing of the rock was due to thermal stresses

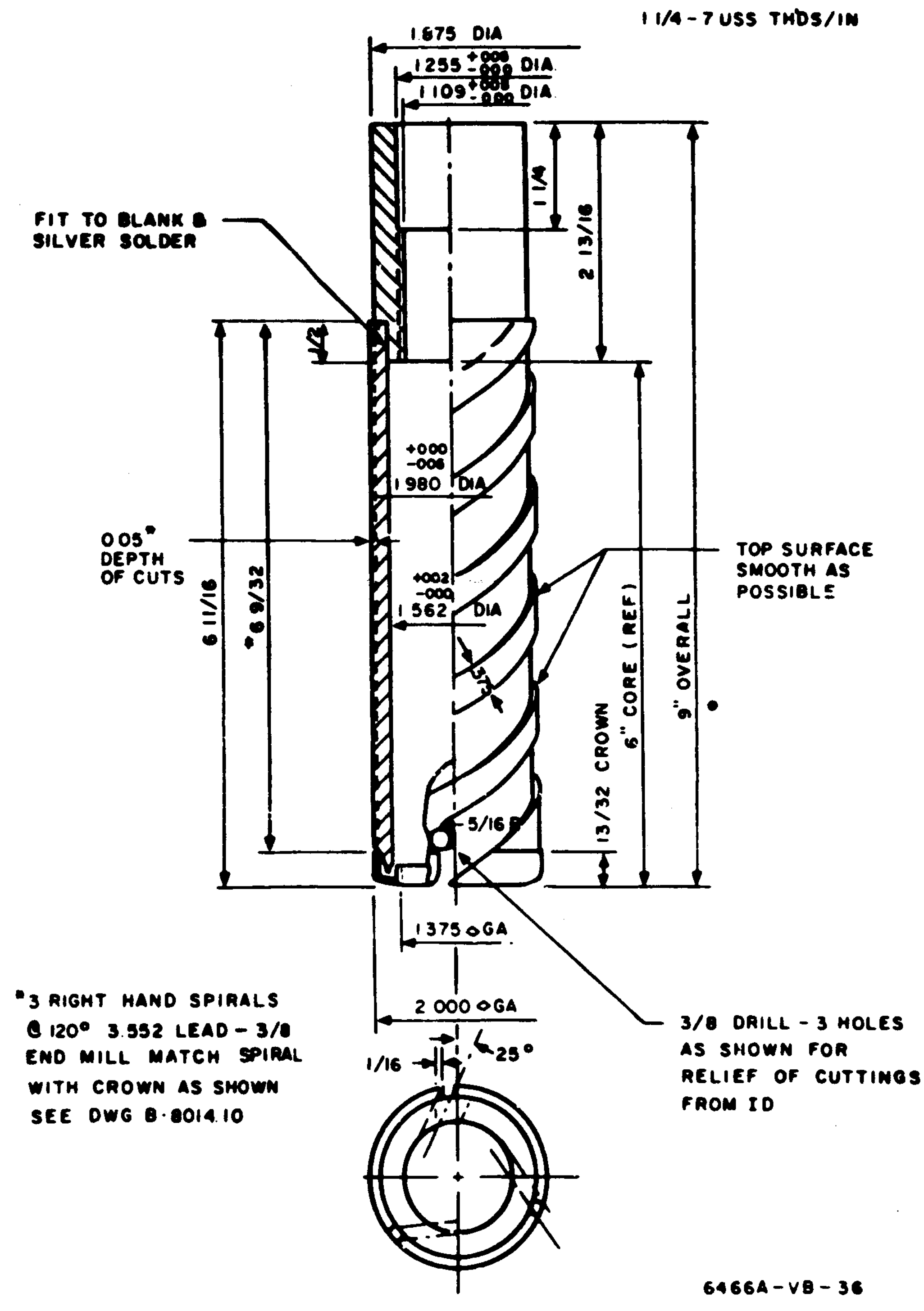


Figure A-12. Auger Flight Bit Design

created during drilling and play in the rig, rather than inadequate chip removal. The penetration made during this test was 2.17 inches with a total core length of 13.05 inches being cut by the bit.

On 9 November 1965, a new bit was installed on the radial arm drill. While attempting to collar the hole, the Morse taper reducing sleeves loosened and caused excessive wobbling of the bit. This wobbling caused the diamonds to be torn out of the mastic, thus quickly overheated, and the test series was terminated.

A.6.3 Summary and Conclusions

This series of tests verified that a limited thrust, variable feed rate advancing mechanism is needed for rotary diamond core drilling. The modified drill rig was found acceptable for providing the necessary thrust needed to demonstrate the feasibility of removing chips with an auger type diamond bit. Chattering observed during earlier tests was reduced by the addition of a flywheel to the drill shaft.

It is felt that the breaking of the core at the end of many of the drill runs was due to thermal stresses produced during drilling and play in the rig itself. The drilling of holes above the crown of the bit did not seem to affect the performance of the bit. These tests did verify the acceptable design of the feasibility bit (design C).

A.7 DRILL BIT LIFE TESTS

A.7.1 Introduction

By the end of 1965, sufficient tests were performed to demonstrate the feasibility of diamond core drilling and chip removal without an external flushing agent in the earth ambient as well as in high vacuum. During the first half of 1966, emphasis was directed at making dry diamond drilling a practical coring technique; that is, investigating a system and bit design that would yield a bit life (total inches of penetration) compatible with the objective of drilling to depth of at least 100 feet.

Analyses of the previous testing indicated that the following areas should be further investigated to extend bit life:

- Efficient chip transport or augering.
- Selection of proper diamond types or shapes for the face stones and the ID and OD gage stones.
- Orientation of the diamonds.
- Means to overcome the detrimental effects of inefficient chip removal.

To obtain the maximum amount of information with minimum expenditure of time and indeed with a ridgedly fixed end date, sequential testing was precluded and a paralleled effort was dictated. Augering tests were begun (see paragraph A. 8) and at the same time diamond types and orientation was investigated and tested.

To avoid the detrimental effects of inefficient augering during the bit and diamond tests, preliminary tests were performed to obtain information to enable continuous monitoring of the drill bit temperature, and the temperature of the bit without cooling. Bits were then constructed with a manifold that permitted internal cooling either by using the latent heat of vaporization of water or convectively cooling by circulating water.

A. 7. 2 Preliminary Thermal Measurements During Rock Drilling With a Dry Diamond Core Drill

A. 7. 2. 1 Introduction

The ability to continuously monitor the temperature of the drill bit while the drill is in operation was an integral part of the Westinghouse lunar drill system concept. During drill system operation, temperature measurements taken at the bottom of the drill hole must be transmitted to the surface and fed into the drill control system.

These tests were conducted at the Westinghouse Aerospace Test Center during the month of December by representatives of the Westinghouse lunar drill program team.

The primary purpose of these tests was to obtain information needed for the development of instrumentation to sense drill bit temperatures and convert this information into a form that can be used as a control function during the drilling operation. A second purpose was to obtain information on the thermal characteristics of a diamond core cutting removal bit while drilling dry without the aid of a thermal control system.

Auger type cutting removal bits (see design C, paragraph A.5) were used with iron-constantan thermocouples emplaced under the bit matrix. On each bit, a thermocouple was connected to a breadboarded telemetering unit which was mounted on a disk clamped to the shank of the drill bit. Mounted in this fashion, the telemetering unit rotated with the bit.

The telemetering unit consisted of a small amplifier feeding a subcarrier oscillator whose modulated output was converted to an RF signal by a miniature transmitter. Changes in bit temperature as referred to a cold junction were thus transmitted as a frequency modulated RF signal to a remote receiver. This receiver then reconverted the information through a discriminator into a voltage output which was recorded on a strip chart recorder. Small batteries mounted on the disk provided a self-contained power supply.

For this series of tests the drill was operated in air at 900 to 920 rpm with a maximum of 400-pound axial thrust. Cores were taken from basalt rock samples without the aid of an external cooling and flushing medium or a thermal control subsystem.

A.7.2.2 Test Procedure

The drill rig used for these tests was the same as that employed in tests reported in paragraphs A.4 and A.6 and in the fourth progress report (Appendixes A and B). Rotational speed was measured with a Strobotac and axial thrust was limited to 400 pounds.

a. Bit serial number U 2880 (Design C, Spiral Surface Set Bit No. 21)

This bit was provided with a thermocouple cemented in a 1/16-inch diameter hole drilled radially into the bit at 1/8 inch from the cutting face. The thermocouple was positioned in one of the chip removal grooves at the trailing edge of an auger flight. To prevent the impedance of the flow of chips up the flight, the thermocouple leads were cemented behind the upper edge of the auger groove.

The bit was eased into the rock and drilling proceeded at 920 rpm until the bit temperature reached 400°F, at which time, the bit was retracted. After cooling in air to 200°F, drilling was continued until a bit temperature of 400°F was again attained. At this point, cutting was stopped and the bit was allowed to cool to 200°F while remaining in the hole. Cutting was then initiated for the third time for a period of 2-1/2 minutes. During this time the bit temperature stabilized at 490°F. The run was terminated at this point due to the thermocouple coming loose. The average penetration rate for this series of runs was 0.97 in/min.

A tabulation of the test data is shown below:

Bit Number 21

Running Time (sec)	Temperature (°F)	Total Depth (in)	Penetration Rate (in/min)	Remarks
0	80	0	-	
61.5	400	7/8	0.87	
141	200	-	-	Bit retracted, cooling in air
80	400	2-3/8	1.13	
121	200	-	-	Bit cooling in hole
64	490	-	-	Temp stabilized
214	490	5-3/4	0.94	Thermocouple lost contact

Total cutting time = 355 sec

Average penetration rate = 0.97 in/min

The thermocouple was replaced and refastened in the same location as previously with silver solder. A drill run to reach maximum bit temperature was then initiated. However, after 2-1/2 inches of penetration, the rock sample fractured and revealed that the crown of the bit was glowing with a dull, cherry red color (1200-1400°F). At this point the test was stopped.

An investigation found that the silver soldering of the thermocouple near the face of the bit has been done without a protective atmosphere. This operation conceivably caused destruction of the diamonds over approximately 1/3 to 1/2 of the cutting area resulting in an overloaded cutting condition on the balance of the diamonds. It was also found that the bit adapter had become loose on the output gear box shaft. The looseness allowed the bit to chatter during collaring and to lose diamonds from the crown of the bit. The result of using a damaged bit which was chattering was the catastropic loss of cutting stones and a subsequent build up of heat due to rubbing of the matrix.

Examination of the test bit revealed that it had become hot enough to deteriorate and smear the matrix with gross loss of diamonds. The telemetered signal was intermittent from the start of this run, and no readable temperatures could be determined from the recording.

b. Bit number 22 - Serial No. U 2881

A backup of the same design as number U 2880 was fitted with an iron-constantan thermocouple which was spot-welded in place. The bit adapter was skimmed to reduce chattering and drill runs similar to those described in paragraph a were initiated. Three consecutive runs were made to a total depth of 4-3/4 inches during which the bit temperature never exceeded 500°F. A final continuous run to a depth of 4 inches at 1 in/min was performed. During this run the temperature rose to 500°F and remained constant at 500°F for the last 3 minutes of cutting. Within 4 seconds after the drill motor was shut down at the end of this run, the bit temperature rose to 600°F.

Examination of the bit revealed no evidence of damage or undue wear. It should be noted that this same bit had a past history of cutting under both air and vacuum conditions, and with the completion of this test it had cut a total of approximately 16 inches of core.

A. 7. 2. 3 Summary and Conclusions

The subject tests have also demonstrated the basic capability of "state-of-the art" instrumentation to link a rotating temperature sensing transducer to a remote control unit without the use of slip-rings and connectors. However, it must still be determined whether or not this method of temperature sensing and transmission will be effective from the bottom of a deep hole (100 ft or greater) in rock formations.

These preliminary tests indicate that the maximum temperature reached during drilling with bits of this type at a rate of 1 inch per minute and 400-pound thrust is approximately 500°F. The 100°F temperature rise noted at the completion of the last drill run is evidence of the amount of generated heat the rock cuttings carry away from the bit.

A. 7. 3 Drill Bit Life of a Cooled Diamond Core Bit

A. 7. 3. 1 Introduction

Additional testing of a thermocouple-instrumented drill bit was completed during the month of February. To obtain instantaneous drill bit temperatures during testing, the breadboarded telemetry system which was described in paragraph A. 7. 2 was again used. A special test bit was constructed with an internal cooling chamber. This arrangement allowed the bit to be filled with a given quantity of water which boiled off during the drill run. In this way, both bit cooling and a measure of the heat generated could be obtained.

These tests were conducted at the Westinghouse Aerospace Test Center during the month of February by representatives of the Westinghouse lunar drill program team.

A. 7. 3. 2 Test Procedure

The test equipment and procedure was basically the same as that employed in tests reported in paragraph A. 7. 2. The drill bit under test (figure A-13) was fabricated from two concentric tubes which yielded an internal cooling chamber of 4.88 in^3. Cooling of the bit was accomplished by the boiling off of the water in the cooling chamber.

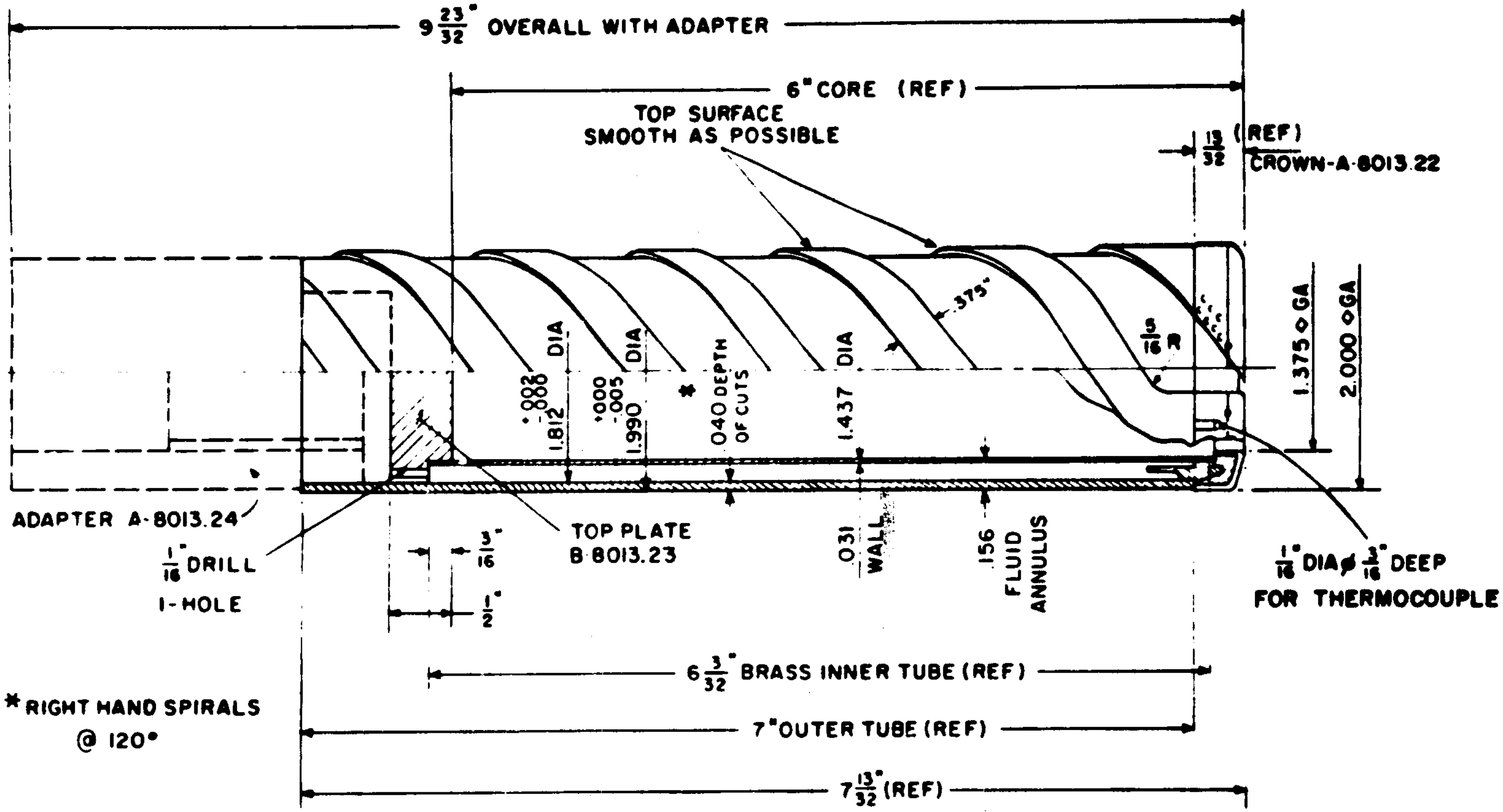


Figure A-13. Test Bit

With 50 cc of water in its cooling chamber, the drill bit was eased into the rock and run at 930 rpm. Because the feed mechanism limited the bit penetration to 1 in/min, the full 400-pound thrust was not applied during cutting. Torque measurements were made with a strain ring instrumented torque table upon which the rock sample was mounted. The maximum torque measured during this run was 2-2/3 to 3.0 lb-ft for a penetration of 5-3/4 inches. The drill bit temperature rose to a maximum of 250°F. During this run 7.5 cc of water was converted to steam.

The drill bit was again filled with water and a second hole drilled. For this run and all others following it, the feed screw on the rig was allowed to get ahead of the drill carriage so that the maximum thrust could be applied. The rotary speed was kept at 920 rpm with a torque of 5.9 lb-ft. With a 400-pound thrust applied, the average penetration rate was 1.8 in/min. The bit temperature stabilized at 342°F until all of the cooling water spurted out of the bit. At this time the temperature rose to 365°F and the run was stopped after a penetration of 5-5/8 inches.

Six more runs were made with this same bit at 920 rpm. The thrust was reduced to 250 pounds for runs number 3 to number 6 in an attempt to increase the bit life. As can be seen in table A-5, the thrust was increased during run number 7. Four thermocouples were mounted on the rock sample to sense rock temperatures during drilling. These rock temperatures are plotted in figure A-14 while the bit matrix temperatures are plotted in figure A-15. The test runs were stopped when the penetration rate dropped to 1/8 in/min and the bit temperature reached 400°F. Examination of the bit showed extensive face wear and loss of diamonds on the ID after a total penetration of approximately 40 inches.

A.7.3.3 Conclusions

These tests have demonstrated the basic ability to extend drill bit life by controlling temperature. During test runs at full power (runs numbers 2-8),

TABLE A-5

SUMMARY OF DRILL BIT TEST DATA

Bit No. 23

Test Run	1	2	3	4	5	6	7	8
Rotary Speed, RPM	930	920	920	920	920	920	920	920
Torque, lb - ft	8/3 to 3	5.9	6.88 6.70 6.27	---	6.25 (3in) 6.70 (3in)	---	5.0	6.7
Maximum Temp °F	250	365	300	350	400 (3 in) 340 (3 in)	---	340 (3 in) 380 (1.5 in)	400
Penetration Rate, in/min	1.0	1.8	1.0	.75	.75 (3 in) .625(3 in)	.625	.375 (3 in) .25 (1.5 in)	.625 to .125
Thrust, lb.	>400	400	250	250	250	250	250 (3 in) 325 (1.5 in)	400

it was noted that the water coolant tended to spurt out of the coolant chamber due to cavitation. This condition prevented consistent cooling of the bit and a measure of the drilling energy breakdown.

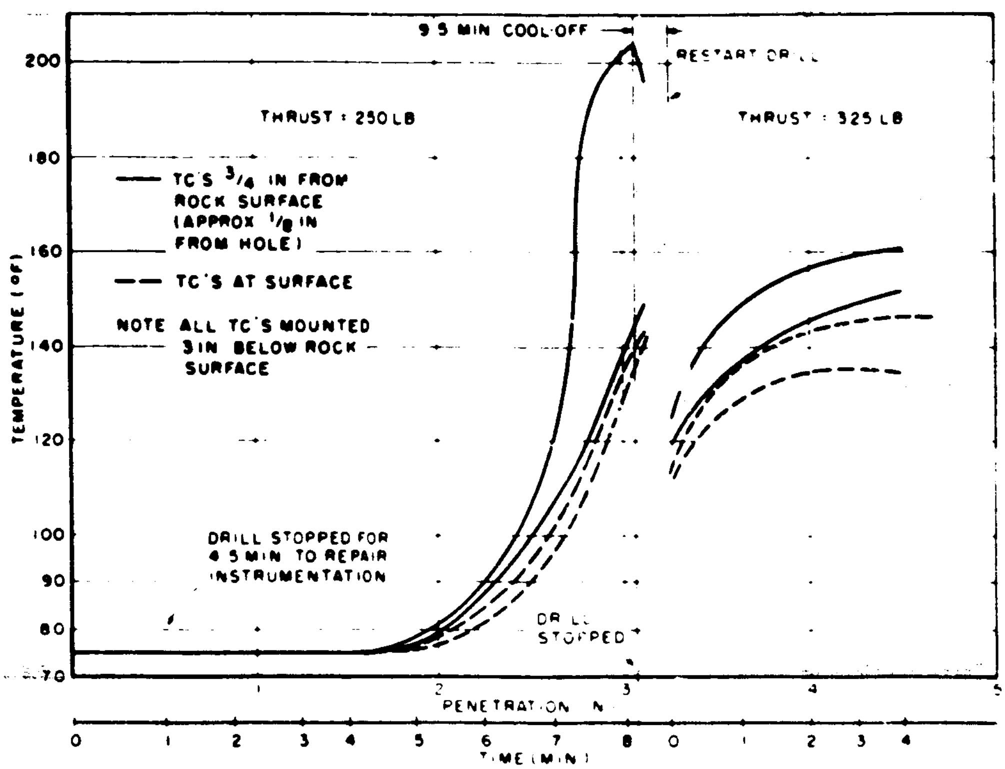


Figure A-14. Rock Temperature, Run No. 7. Bit No. 23

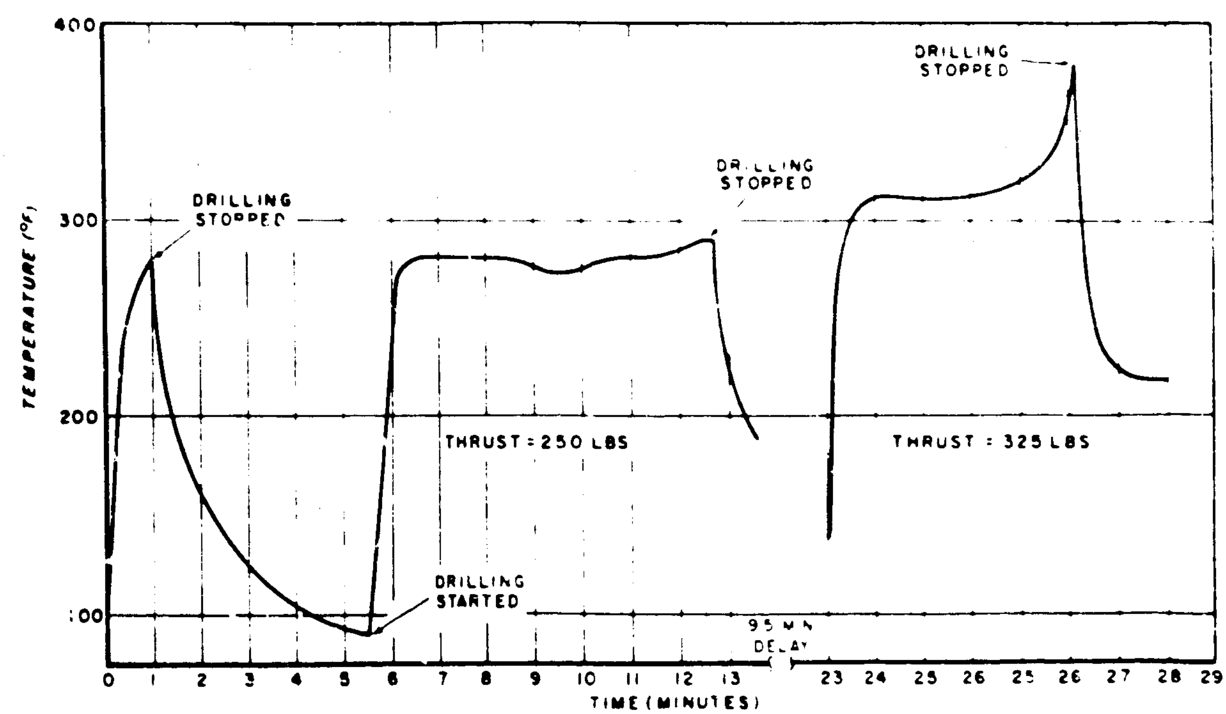


Figure A-15. Matrix Temperature, Run No. 7. Bit No. 23

A.7.4 Drill Bit Life of Water-Cooled Diamond Core Bit and of Spiral Surface Set Bit

A.7.4.1 Introduction

From March through June, 1966 five additional drill bit life tests were performed. Three of the bits used were similar in construction to the bits used for the tests reported in paragraph A.7.3 (water vaporization cooling). However, in these tests, water was circulated through the bit for cooling. The last two bits tested had the spiral surface set design used previously, however, the diamonds were oriented in the direction of cutting. The gage stones were an approximate cubic and the face stones were octahedral.

A.7.4.2 Tests Performed At Aerospace Test Center

Tests to determine the maximum drill bit life while operating in air at a matrix temperature of 300°F or less were attempted during the month of March and April at the Aerospace Test Center. The three drill bits under test were the spiral surface set type having selected and oriented diamonds in the crown. The bits were cooled by a forced water system.

a. Bit No. 24 - At the beginning of the test, it was found that the bit would not penetrate at more than 0.5 in/min. The test was stopped and the drill bit was removed for inspection. An examination of the bit revealed that both this bit and its backup were "matrix-bound." That is, a majority of the diamonds were completely covered by the matrix material (tungsten carbide) and thus had no cutting exposure. Even though the first test bit had previously been water-honed to increase the diamond to matrix clearance, the honing process had failed to remove the excess matrix from the ID gage stones. Therefore, the bit did not cut properly.

b. Bit No. 25 - Before this backup test bit was run, it was decided to sand-blast the bit crown to increase the diamond exposure. This sandblasting, which was done by a contractor outside of Westinghouse was not performed properly and the bit was damaged.

Both drill bits were returned to Longyear for inspection by a diamond expert. Steps were also taken to insure that the diamond bit manufacturer would correct manufacturing defects such as matrix-bound stones.

c. Bit No. 26 - During a checkout of the test setup prior to test start-up, it was found that water leakage was occurring at a number of places in the bit cooling chamber. Temporary patching with soft solder was performed and a pressure test of the bit was made. At this point, the bit was deemed ready for drill tests.

Drilling proceded normally through precollared 6-in basalt samples until a total depth of 35 inches was attained. During this time, penetration rates as high as 2-in/min were recorded with bit matrix temperatures never exceeding 250°F. Effective cooling was obtained by maintaining a 0.3 gpm flow of water through the bit cooling manifold. At this point, however, the penetration rate abruptly dropped to less than 1/4 in/min. Testing was stopped and the bit was removed and inspected. Even though the face stones appeared to be in good shape, the condition of the ID gage stones could not be determined because of the presence of the solder. The solder was then removed and drilling attempted, but no appreciable penetration was noted. The drill bit was again inspected and appreciable wear on the ID gage stones as well as loss of some of these diamonds was observed.

Steps were taken to determine why the drill bit failed so abruptly after 35 inches of penetration and how to insure that a reoccurrence of this failure will not take place. The two possible causes were: (1) poor manufacturing techniques, particularly in the orientation and embedding of the ID gage stones, (2) the detrimental effects of the solder used to patch the leaky bit. Diamond experts were asked to inspect the subject bit for signs of graphitization as well as to check the quality and orientation of the diamonds. The bit manufacturer was notified of the difficulties encountered during testing.

This terminated the bit life testing at the Aerospace Test Facility. However, the information gain in these tests was factored into the construction of two more bits that were tested at the Bureau of Mines. The Bureau of Mines test of these two bits is contained in the following paragraph A.7.4.3.

A.7.4.3 Drill Bit Life Tests At Bureau Of Mines

Arrangements were made to conduct life tests of the latest drill bit design at the Bureau of Mines, Twin Cities Research Center during the month of June. This latest bit design was based on the recommendations of Dr. Long and Pflieder* after their analysis of the previous bit (bit no. 26), which failed at 35 inches. The following changes were made to the bit:

a. The cubical gage stones were reoriented so that the thrust is applied to an edge of the cube rather than to a corner as had previously been done.

b. The previous test drill which used dodecahedral face diamonds has been replaced with one using octahedral stones.

c. The bit annulus shape and size was modified to obtain a better mechanical connection between the bit crown and shank. This change should prevent the type of water leakage observed during the last bit test.

The length of the test bits was increased to 15 inches which would permit 12-inch continuous cuts to be made. However, only 8-inch continuous cuts were made due to the limited stroke of the Carlton Radial Arm Drill used for the test. The auger depth had also been increased to 0.030 inch which was the depth to be used for the engineering model auger flights.

During bit life tests, the parameters that should be measured to allow analysis of drill performance, the data rate required and expected range of parameters are listed in table A-6.

This test series was instrumented as shown in table A-6. However, instrumentation difficulties were encountered during the test preparation and first test run, preventing the temperature gradient across the matrix and the torque to be measured. A readout of the bit matrix temperature was obtained

* Dr. A.E. Long, Bureau of Mines, Washington D.C.
Dr. E. Pflieder, Chairman of the Dept. of Mining, University of Minn.

TABLE A-6

DRILL PERFORMANCE MEASUREMENTS

Parameter	Instrumentation	Location	* Data Rate	Range of Variables
Torque	Strain Gage	Swivel joint Adapter	Continuous	0-10 lb-ft
RPM	Strobotac	Drill Shaft	1/min	800-1200 rpm
Penetration Rate	Stop watch, scale, & linear pot.	----	2/min	1/4 to 3 in/min
Thrust	Fixed at Test Start	----	----	300 to 400 lb
Temperature	(1) Thermistor (2) Thermistor (3) Thermocouple (4) Thermocouple	Bit (matrix Bit (manifold) Input water line Output water line	Cont. Cont. Recorder max. Recorder max.	100-600°F ΔT, 0-50°F ΔT, 0-30°F
Flow Rate	Flow meter	Input water line 1/min		0.02-0.3 gal/min

* At penetration rates of greater than 1 in/min the data rate was adjusted to yield 10 to 12 readings per run.

for the first 30 seconds of drilling. This temperature reading indicated a stabilized matrix temperature of 300°F, which coincided with previous temperature measurements. During the whole test series, the water coolant was maintained at a constant 0.3-gpm flow rate.

An examination of bit no. 27 before testing revealed that two of the three segments making up the face were raised above the third segment. During rock coring with this bit, chattering and excessive runout were noticed. The initial penetration rate was 2.9 in/min at 400-pound thrust and 1140 rpm. At end of life, the cumulative penetration was 41-1/4 inches. At this time, an examination of the bit revealed signs of rubbing on the matrix of the two raised segments and little sign of wear on the third segment.

Before bit no. 28 was tested, the runout was carefully brought within a tolerance of 0.005 inch and the face inspected. Both of these factors which has affected the life of the first bit (bit no. 1) were not present during the test of the second bit (bit no. 2). To reduce the penetration rate, the bit was first run at 300-pound thrust and 820 rpm. Drilling was smooth throughout the test and all cores taken were exceedingly smooth. The initial penetration rate was 3.0 in/min and with an increase of thrust to 400 pounds after 20 inches of penetration; the rate remained at or above 2 in/min for the following 70 inches of penetration (Cumulative depth = 90 inches). The total bit life for bit no. 28 was 123 inches of penetration. It is felt that if this bit had been used to drill a continuous 10-foot hole instead of a number of 8-inch holes, the bit life would have been appreciably increased.

The curves of penetration rate as a function of cumulative distance drilled is shown in figure A-16. This curve shows the average penetration for each core and the contrasting difference between "wearout" of bit no. 28 and the catastrophic failure of bit no. 27.

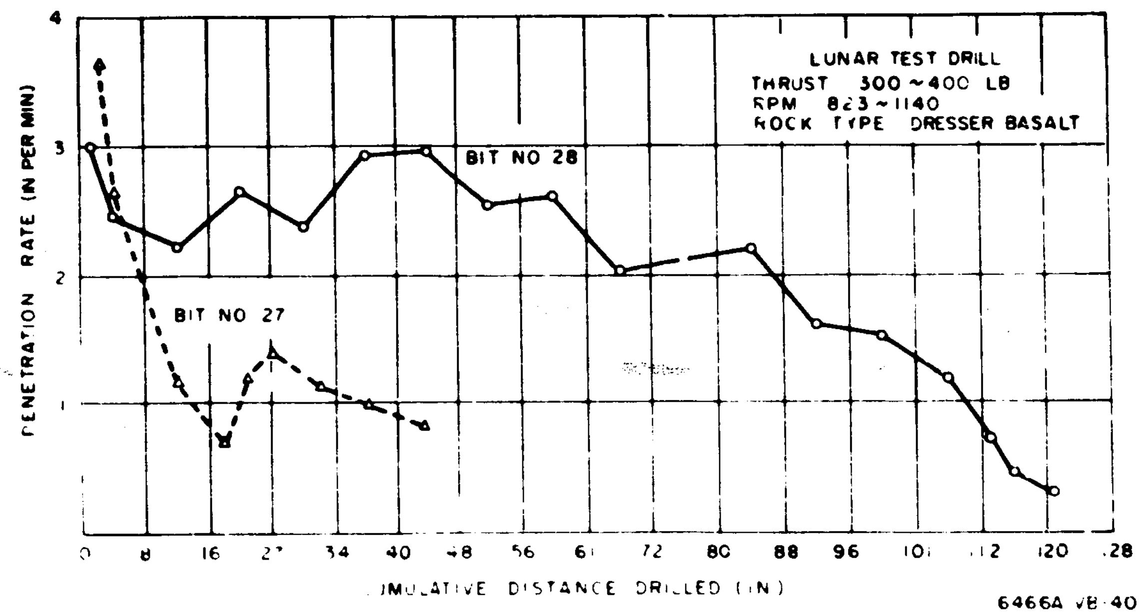


Figure A-16. Penetration Rate as a function of Cumulative Distance Drilled

A. 8 LUNAR DRILL BIT TESTING DURING SYSTEM PREACCEPTANCE TESTING

A. 8. 1 Purpose

The purpose of the bit testing during this period was to check the bit's function as an integral part of the Lunar Drill System and to check a slight design change. Bits 29 to 34 were essentially of the same design as bit 28 which drilled 123 inches in basalt except that the crown surface was interruped by five chip channels instead of three to provide more channels for chip removal to the bit circumference. The number of anger flights was changed to correspond with the number of channels.

A. 8. 2 Test Plan

The test plan for testing the bits during the System Preacceptance Testing is presented below. The test plan was followed until the equipment problems occurred.

TEST PLAN

LUNAR DRILL BIT TESTING DURING SYSTEM PREACCEPTANCE TESTING

1. PURPOSE

To confirm that the drill bit design will permit a 50-inch hole to be drilled in basalt and to evaluate the overall performance of the previously integrated lunar drill components.

2. PROCEDURE

2. 1 PREREQUISITES

The complete unit will have been integrated, mounted and tested and appropriate temporary fixes of problem areas before the subject tests commence.

2.1.1 Auxiliary Equipment

The following support equipment is required:

a. 100-volt power supply, regulator, and circuit breaker

b. 28-volt regulated power supply

c. Motor starter

d. Means for breaking and retrieving the core and broken core pieces after each bit withdrawal.

2.2 REQUIRED INSTRUMENTATION AND DATA

The following instrumentation shall be provided and the resultant data recorded to check out the performance of the lunar drill bit and engineering mode (table 2-1).

TABLE 2-1

REQUIRED INSTRUMENTATION AND DATA

Instrumentation	Data to be Recorded	Recording Method	Recording Frequency
1. Voltmeter and ammeter	Input power	Hand	1-reading unloaded 1-reading during each feathering operation 1-reading/min other times
2. Thermocouples	ΔT motor coolant	Recorder	Cont
3. Thermocouples	ΔT bit coolant	Recorder	Cont
4. Strobotac	RPM	Hand	1-unloaded 1-each feathering operation 1/min other times
5. Feed Rate Sensor Penetration Rate		Recorder	Cont
6. Thrust Sensors on Frame	Thrust	Recorder	Cont
7. Thermistor	Bit temperature	Recorder	Cont

TABLE 2-1 (Continued)

Instrumentation	Data to be Recorded	Recording Method	Recording Frequency
8. -	Diamond condition	Visual	Every bit withdrawal
9. Thermometer	Ambient temperature	Hand	Once
10. Flow meter	Motor coolant flow rate	Hand	1/minute

2.3 OPERATING CONDITIONS

Earth ambient temperature and pressure will be the operating environment.

2.4 TEST SEQUENCE

Upon completion of the mounting of the drill system and installation of the rock sample, support equipment, and instrumentation, the following test operational procedure is to be followed to drill a 50-inch hole in basalt and break and retrieve a portion of the core.

1. Feather hole to the depth of 3/8 inch. The hole is to be feathered in using a nontest bit operating at a 1/4-inch feed rate and approximately 60 pounds of thrust. The bit need not be cooled by an internal coolant. The steadying bushing shall be [illegible]loyed. Observations should be made of the drilling parameters indicated by the control unit and the operating characteristics of the feed rate sensor, the steadying bushing-core barrel combination, drill frame, and motor coolant. These results should be recorded.

2. Install the experimental core barrel and bit no. 1 combination with the repositioned internal thermistor after ensuring its water tightness and electrical continuity. Do not install the inner core barrel.

3. Lower bit so that its crown is approximately in the same plane as the rock surface and above the hole feathered in step 1. Start water flow through the drill string at a rate of 0.1 gallon/min at 30 psi maximum.

4. Start drill in feathering mode (1/4 in/min and 40-pounds thrust and drill rotating). Feather in again 1/4 inch beyond the first feathering depth.

5. Increase feed rate slowly to 1-1/2 in/min, then increase thrust setting slowly to 400 pounds. Mark exact depth on measuring tape attached to the drill drive mechanism at the start and finish of each drilling increment.

6. At the 6-inch hole depth, retract the drill. Back-ream for the first 1/4 inch only.

7. Retract the drill to the highest point of motor gearbox travel. Photograph the drill bit.

8. Examine the drill bit.

9. Probe for and remove any stone chips which may lay in the kerf.

10. Start drill rotating and move it down in the feathering mode over the core for the first 1/4 inch. Stop drill rotation and slide it down over the core until 1/2 inch from previous drilling stop point at a rate of 4 in/min.

11. Start drill in the feathering mode and drill in that mode for 1/4 inch after contact with the solid rock is made.

12. Increase feed rate slowly to 1-1/2 in/min and increase thrust slowly to 400 pounds. After drilling 6 inches (for a total of 1 foot), increase feed rate slowly to 3 in/min.

13. If the drilling operating appears satisfactory, increase the feed rate to 4 in/min. After drilling about 6 inches, clean the chips from the rock surface. Continue drilling until the 18-inch hole depth is reached.

14. The drill bit should be withdrawn with the drill control set to BACK REAM for the first 1/4 inches only.

15. Retract the drill bit to its highest position.

16. Examine the drill bit.

17. Insert core breaking wedge and break core. Extract core.

18. Vacuum hole and extract any large chips not picked up by the vacuum device. Probe for and remove any stone chip which may lay in the kerf.

19. Ascertain height of broken core stub from the rock surface.

20. Lower drill without rotating until 1/2 inch from top of stub at rate of 4 in/min and start drill in the feathering mode. Drill in this mode for 1/4 inch after contact with the solid rock is made.

21. Increase feed rate slowly to 3 in/min and increase set thrust slowly to 400 pounds.

22. If the drilling operation appears satisfactory, increase feed rate to 4 in/min. After drilling 6 inches, clean chips from rock. Continue until the 30-inch hole depth is reached.

23. Withdraw the drill bit with the drill set to BACK REAM for the first 1/4 inch only.

24. Retract drill bit to its highest position.

25. Examine the drill bit.

26. Probe for and remove any stone chips which may lay in the kerf.

27. Ascertain height of core stub from the rock surface.

28. Lower drill w[illegible]ut rotating until 1/2 inch from top of stub at [illegible] 4 inches/min and sta[illegible] drill in the feathering mode. Drill in this mode until 1/4 inch past top of stub[illegible] Stop drill rotation and slide drill down over the core until 1/2 inch from previous drill stopping point at a rate of 4 in/min.

29. Start drill in the feathering mode and drill in that mode for 1/4 inch after contact with the solid rock is made.

30. Increase feed rate slowly to 3 in/min and increase thrust slowly to 400 pounds. If the drilling operation appears satisfactory, increase feed rate to 4 in/min. After drilling 6 inches, clean chips from the rock surface. Continue drilling until the 42-inch hole depth is reached.

31. Withdraw the drill bit with the drill set to BACK REAM for the first 1/4 inch only.

32. Retract the drill bit to its highest position.

33. Examine the drill bit.

34. **Insert core breaking wedge and break the core. Extract the core.**

35. **Vacuum the hole and extract any large chips not picked up by the vacuum device.**

36. **Ascertain height of the broken core stub from the rock surface.**

37. **Spread waterproof covering over entire top of rock, secure the drill cooling system and remove swivel joint.**

38. **Insert inner core barrel in outer core barrel with hoist and overshot.**

39. **Replace swivel joint.**

40. Start the drill cooling system and allow to run.

41. Wipe dry the drill rig and carefully remove the waterproof covering so as to keep water from entering the hole.

42. Lower the drill without rotating until 1/2 inch from top of stub at rate of 4 in/min and start drill in feathering mode. Drill in this mode for 1/4 inch after contact with the solid rock is made.

43. Increase feed rate slowly to 3 in/min and increase thrust slowly to 400 pounds. If the drilling operation appears satisfactory, increase feed rate to 4 in/min. After drilling 4 inches, clean chips from rock surface. Continue drilling until 50-inch depth is reached and ream in place for 15 seconds.

44. Set drill in break core mode and break the core.

45. Remove the swivel joint and lower the overshot until it mates with the contract plate of the inner core barrel.

46. Inch up until hoist cable is taut. Then permit hoist to lift the inner core barrel. Remove the inner core barrel from the hoist.

47. Withdraw the drill bit to its highest position.

48. Examine the drill bit.

49. Remove the core from the inner core barrel.

A.8.3 Bits 29, 30, and 31

These bits did not meet the quality control specifications, but were utilized to obtain as much data as possible. Bit 29 exhibited some auger flights mismatch with that of the core barrel. Excessive torquing with the Parmalee wrenches resulted in the crown separating from the manifold at the braze line. The bit was repaired locally but had excessive runout and was employed only as a feathering bit.

Bits 30 and 31 were instrumented by inserting a thermistor in a radial hole drilled in the exterior of the matrix. As each bit was used, the signal leads were run up under one auger flight and sealed in place with epoxy cement. The leads then entered a modified core barrel adapter. Each of these bits had to be resealed with a solder because of water leaks at the braze line. Each of the bits had excessive runout (approximately 0.015-0.020 inch) partly due to the excessive torquing to line up the auger flights and to make the bit-core barrel seal and partly due to manufacturing anomalies.

Both bits failed during feathering due to the ID gage stones pulling out possibly due to the runout effect on individual stones and to vibration resulting from the runout.

A.8.4 Bits 32, 33, and 34

A.8.4.1 Introduction

These bits were made in accordance with the standards and drawings shown in figure A-17. However, these bits also had minor deficiencies which had to be corrected prior to use. The bits were examined by Dr. Long, US Bureau of Mines for quality of workmanship, orientation and type of crystal. The stones appeared to be well set although the orientation of the stones could have been improved. There was a blockage in bit 33 which had to be corrected and there were some oversize threads. The runout was held to less than 0.002 inch.

A 52-inch piece of basalt was procured from Dresser Wisconsin quarries with a Shore hardness of 79 and a compressive strength of 43,000 psi. It

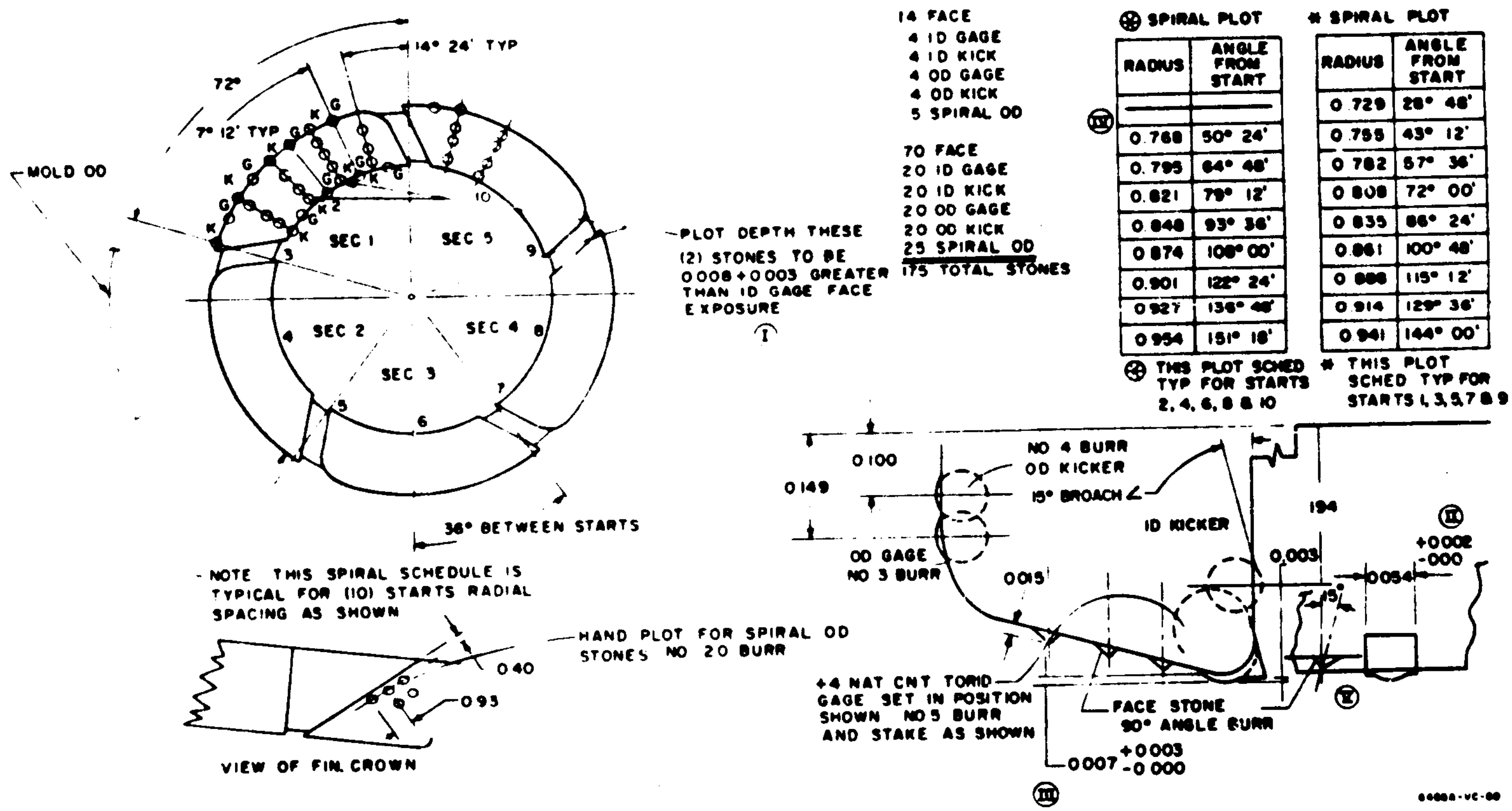


Figure A-17. Drawing of Plot Sketch Without Keys was mounted in concrete and bolted to the floor. The surface had been sawn flat (see figure 1-1). Bit 29 was used to feather the hole to a depth of 3/8 inch. The experimental core barrel could not be sealed to bit 32 or to the adapter.

It was decided to drill without coolant for the following reasons:

a. It was difficult to make the adapter core barrel and core barrel bit joints watertight for a gravity head. After several attempts with the copper gaskets, the string still leaked badly.

b. The lack of integrity of the water channel seal was shorting out the bit instrumentation.

c. A review of the reports of previous drilling tests and particularly of the Bureau of Mines 10-foot test showed that approximately 500 watts were being removed from the bit and auger flights by the water cooling. A matrix area vs the auger flight area comparison indicated that the bit matrix contributed probably less than 50 watts to the water cooling system. Since the chips carry the heat away from the cutting surface, the bit and auger flight system probably would stabilize at a slightly higher temperature but still considerably under crown temperatures which would prove damaging.

d. There were three test bits available. In view of the delay in the shipping of a deliverable core barrel, which was to be used in the testing of the grease-coupled instrumentation contacts which tied in with the adequacy of the water sealing approach, a possible sacrifice of one bit to get system operation information appeared to be a good risk.

e. The potential weight reduction and reliability improvements in taking the "no coolant" approach also made the risk of the possible loss of one bit quite palatable. These were:

(1) Elimination of leaking problems

(2) Examination of the rotary joint

(3) Elimination of the radiator hoses and valves

(4) No lunar environment-coolant interface problems

(5) No coolant weight

(6) Elimination of the erection time for the radiator and hoses, rotary point, valve assembly

(7) The elimination of handling of the rotary joint, valve assembly, gaskets, etc, during drilling.

A.8.4.2 Test Procedure

a. The thermistor output was calibrated against a known temperature applied to the bit. The heat was applied by burying the bit in a bucket of sand heated by an electric heater. The bit exterior face was checked by an attached thermocouple.

b. Thermal paints were applied in small thin dabs to cover the expected temperature ranges.

c. Bit 29 was used to collar a new hole to a depth of 3/8 inch.

d. Bit 32 was feathered in for another 1/4 inch and then a feed rate of 1 in/min was set. After one inch, the bit was removed from the hole and examined and a replica made. The recorder indicated that the temperature did not exceed 340°F internally and the thermal paints indicated that the external surface did not exceed this figure. The matrix was cool enough to keep one's finger in contact with it when the string was removed. The core barrel at about 5 inches up from the matrix was too hot to touch.

e. Another 2 inches were drilled before the drill shut off due to a core block signal. Examination of the bit thermal paint showed again that the 350°F was not exceeded. However, there was a burned area on a bit auger flight just above the matrix and another area above 3/8 inch above the bit-auger flight junction. Some of the dental cement sealing this junction (filling a space of some 0.030 inch caused by the internal gasket used to line up the core barrel internal channels with the bit channels) had extruded out and may have caused some chip stoppage. In the ID of the bit, the copper gasket has extruded slightly, but appeared not to be hitting the core. The auger flights between the bit and core barrel were not exactly lined up. This offset was required to compensate for core barrel faults and to line up the internal channels to get the instrumentation leads to the bit. The experimental core barrel had the normal signal channel blocked and a shielded set of signal leads had to be inserted through a water channel.

f. The bit-core barrel combination was removed. The stones were examined under a 15 X magnification and showed no damage except for the chip fractures. These had occurred during an earlier feathering and had been reported by Christiansen Diamond Products during the rework of the bit. The bit-core barrel combination was then indicated for runout - first using V-block supports and then held in a collet in a lathe. It was apparent that the bit axis was at a small angle to the core barrel axis; the core barrel was not circular in cross section and was larger in diameter at some points than the OD gage stone circle. The bit tilt with respect to the core barrel was reduced by putting in a nonextrudable stainless steel washer of a thickness calculated to even up the auger flights. The instrumentation had to be removed to accomplish this because the bit and core barrel internal channels would no longer line up when the flights lined up. The bit and barrel were then set up in a lathe and the auger flights were ground for the first 18 inches until they were 0.005 inch below the highest OD diamond exposure at all points.

g. A second drill run was attempted, using thermal paints as temperature indicators. At 1 in/min feed rate setting and 175 pound thrust, the bit would not cut. There was another control cutoff related to underfeed. Examination of the bit showed some minor stone burnishing.

h. Bit 33 was attached but could not be made to cut without system shutdown. A check indicated that the upper thrust limit was set too low. The drill system drilled well at 1/4, 1 and 2 in/minute. Bit 33 was used to drill an additional 3 inches. At this point, the drill motor failed. At no time did the bit, when cutting, go over 350°F. At each drill string withdrawal, which occurred less than 1 minute after rotation ceased, the bit flights were touched with no real discomfort as the bit came out of the hole.

Bit 33 was examined and appeared in good condition. The air-cooled motor was installed and a temporary fix for a solid lubricant idler gear and bearing retainer failure was made. The gear box was lubricated, where the idler gears were removed, with a grease made of Apiezon H grease, zinc oxide and molybdenum disulphide in proportions by volume of 8:3:1.

Drilling was resumed using bit 32 for another 3 inches. Drilling was stopped to replace a loose screw in the motor pinion. Drilling was resumed to a depth of 22 inches. The bit had bound in the hole due to a chip blockage. The blockage apparently caused a binding action which created frictional heat. The heat expanded the bit until it bound against the side of the hole. The abrupt stoppage had torqued the bit further onto the core barrel forcing the inside structure of the bit downward and cracking the crown (see figure 2-4). The bit stones still appeared to be in good condition.

A. 8. 5 Acceptance Demonstrations

A new hole was collared using bit 29, in the presence of Mr. Bruce Hall, Corps of Engineers, who was observing for NASA, Huntsville, using a feed rate of 1/4 inch/minute and a 60-pound thrust. Bit 33 was sealed by unconventional means to the experimental core barrel and filled with water. A hole 6-11/16 inch deep was drilled, but the test was stopped when a thrust sensor failed. Upon drilling resumption an unusual vibration occurred. Examination showed that water had leaked into the hole producing a chip mud which appeared to cause the bit and core barrel to seize intermittently.

A new hole was collared using bit 29 in the presence of Messrs Lundy and Tepool of NASA, Huntsville. Bit 34 was used on the experimental core barrel, but no water cooling was employed.

A hole 2 inches deep was drilled. The drill string was raised and the bit inspected. Another 3 inches was drilled and then the inner core barrel was installed. The hole was deepened another 1.2 inches for a total of 6-1/4 inches. The core was broken and recovered. The core was in one piece and very smooth.

All drilling other than feathering was performed with a feed rate of 2 inches/minute and 250-pound thrust command settings. The bit appeared to be in excellent condition.

A. 8. 6 Conclusions

The limited degree of hole footage during System Preacceptance and Acceptance Demonstration testing appears to indicate:

a. The hole should be collared with a separate bit.

b. A steadying bushing should be used for the initial core barrel length.

c. The maximum feed rate for good operation seems to be at a feed rate command setting of 2 inches/minute.

d. The bit and core barrel must have 0.005 inch minimum clearance between the highest OD diamonds and auger flights to elevate the chips without binding.

e. The junction of the bit-core barrel must be smooth or chip binding will occur.

f. Whether the bit is cooled with internal coolant or not, the temperature of the matrix and auger flights does not rise above 350°F with normal chip removal.

g. The addition of water to the chips in the hole produces a chip binding action.

h. The core barrel and bit must have extremely close tolerances with respect to out of roundness, bowing and twist.

i. The bit matrix should be in a plane as perpendicular to the axis of rotation as mechanically possible.

j. Care must be taken in assembling the bit to the core barrel not to distort the bit with the wrenches.

k. Once the hole is feathered, the drill bit should be brought immediately to the drilling settings.

APPENDIX B

FEASIBILITY OF ROTARY JOINT OPERATION IN VACUUM ENVIRONMENT

B.1 INTRODUCTION

The thermal control system for the Westinghouse concept of the lunar drill requires a transfer of fluid and vapor from a stationary radiator and reservoir to a rotating drill string. Westinghouse has considered two swivel joints - the Type E Barco Joint and the Type S Johnson Joint. With slight modifications either one of these joints could be used for the drill model. In either case, a self-seating carbon to steel seal should be used. This appendix describes the test of a Barco Type E Rotary Joint under vacuum conditions.

The test was conducted at the Westinghouse Aerospace Test Center or 19 November to 1 December 1965 by representatives of the Westinghouse lunar drill program team.

The rotary joint under test was a Type E Rotary Joint manufactured by the Barco Manufacturing Company for the E.J. Longyear Company. The joint was modified by the addition of a teflon O-ring to provide a static seal compatible with the vacuum environment. The primary moving seal is self-aligning carbon to stainless steel, which is capable of operation at 250 psi. A detailed description of this seal is found in paragraph 2.2 of the Third Progress Report.

Rotation of the seal under vacuum was provided by a 1/2-hp, 840-rpm, induction motor. The vacuum environment was provided by two different vacuum systems in order to allow testing at two discrete vacuum levels. For a pressure level of 300 microns, a 30-inch diameter by 5-feet long reentry chamber having a mechanical pump rated at 20 microns pressure was used. For higher vacuum tests (1×10^{-4} Torr), a 3-foot diameter by 4-foot long thermal vacuum chamber using two oil diffusion pumps capable of 1×10^{-8} Torr operation was used.

The setup used in both test chambers was basically the same. A tube and pressure gauge were added above the joint housing and the joint rotary shaft was connected with a flexible coupling to the motor output shaft.

B.2 SUMMARY

The operation of a rotary joint with an internal pressure of 250 psi has been demonstrated at vacuums of 200 microns and 1.6×10^{-4} Torr respectively. The measured leakage rate was 0.85 gram/hr with observable leakage taking place only at the beginning of pumpdown. Once the vacuum chamber being used reached its end pressure, the rotary joint was rotated at 840 rpm for at least 30 minutes. During this period no leakage or ice formation was observed. Visual examination of the dynamic seal did not show any evidence of deterioration due to ice.

B.3 TEST PROCEDURE

For each test the rotary joint (joint no. 1) was tested with dry nitrogen in earth atmosphere for leakage at 250 psi. The joint was then filled with water (about 20 ml) and pressurized to 235 psi (250 psi at vacuum) with dry nitrogen. At this point the rotary joint, pressure gage, and associated piping were weighed to an accuracy of 0.01 gram. After runs of at least 30 minutes at 840 rpm and 250 psi under vacuum, the apparatus was reweighed and the leakage rate calculated.

Both vacuum chambers used for testing were equipped with a window which allowed observation of the rotary joint and pressure gage throughout the tests. The temperature of the rotary joint housing, motor frame, and motor oil pump were monitored by means of thermocouples.

a. For this preliminary test the vacuum chamber was pumped down and checked for leaks. The rotary joint apparatus was filled with water, pressurized and installed in the chamber. At this time a pumpdown was initiated. At the very beginning of the pumpdown, a few drops of water were observed coming out of the joint housing. This slight leakage, which was probably due to water that had been forced through the seal when the joint was pressurized, stopped after 30 seconds. No leakage was observed for the duration of this first test (105 minutes). The gage pressure was monitored during this test, but leakage rate was not measured. The temperature and pressure of the rotary joint rose to values of 176°F and 267 psi respectively indicating a tight seal at a chamber pressure of 300 microns Inspection of the disassembled rotary joint at the end of this test revealed the presence of a graphite and water emulsion on the inside of the joint housing.

b. A second test in the vacuum chamber was performed with the rotary joint cleaned and repressurized at 234 psi. Once again water drops were observed for about 30 seconds at the beginning of the test. The rotary joint was run for 105 minutes at a vacuum of 300 microns. There was no leakage observed for the duration of the test as the temperature and pressure of the joint rose to 182°F and 255 psi respectively. Measured water loss was 1.49 grams or 0.85 gr/hr. A plot of the observed rotary joint temperature rise is shown in figure B-1. At the completion of this test the graphite water emulsion noted earlier was not in evidence.

c. For this test the apparatus was pressurized and installed in the thermal-vacuum chamber. To prevent possible frosting the seal was kept at 100°F with a strip heater wrapped around the swivel joint housing. The chamber was pumped down to a pressure of 1.6×10^{-4} Torr before the rotary joint drive motor was turned on. During this 35-minute test, the vacuum pressure leveled off at 3.0×10^{-4} Torr as the rotary joint temperature and pressure reached values of 198°F and 284 psi respectively. Data taken

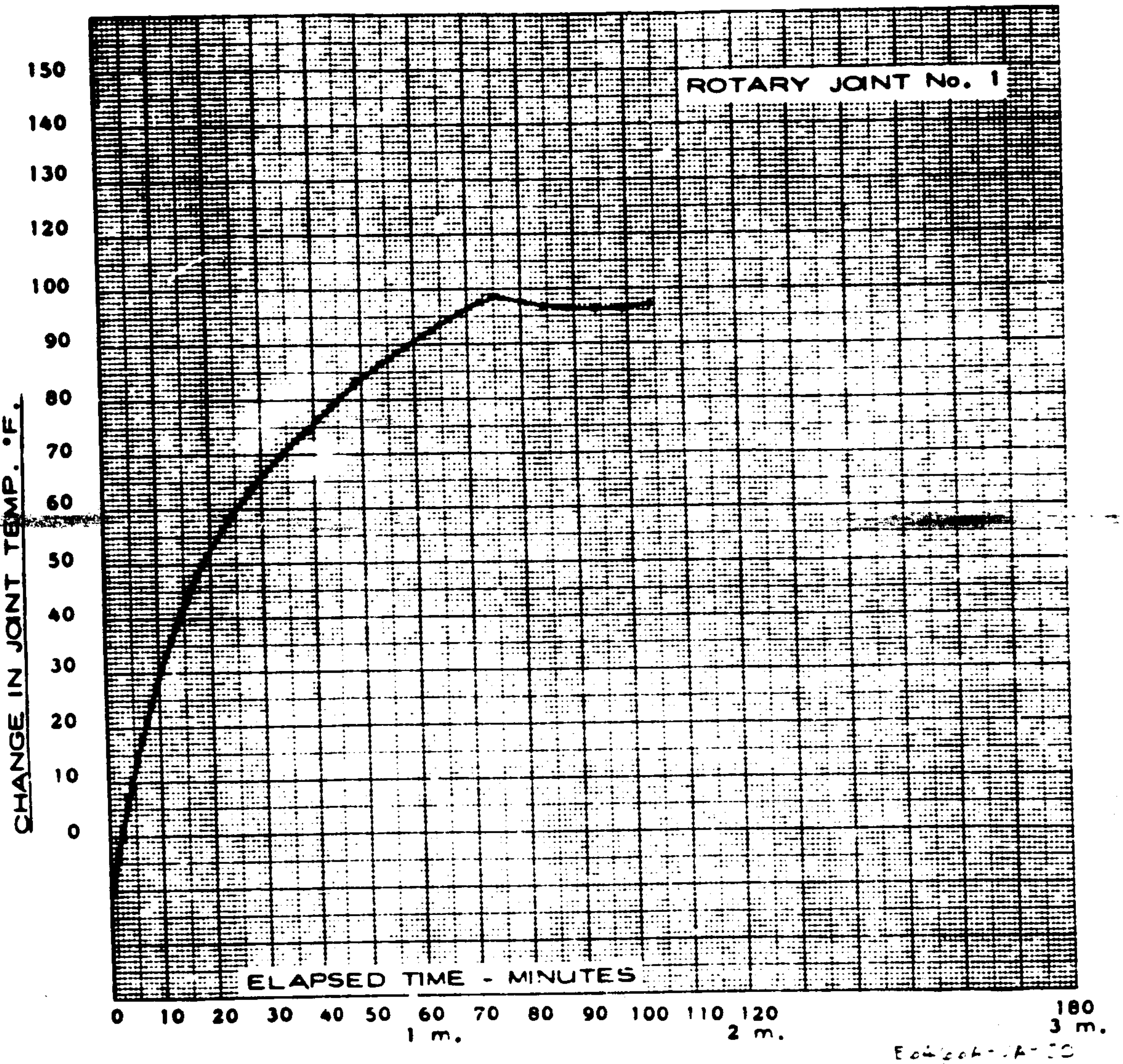


Figure B-1. Time vs ΔT for Test No. 2 at 300 Microns during this test is plotted in figure B-2 to show the direct correlation of pressure to temperature. There were no signs of leakage or ice formation observed while the chamber was in the 10^{-4} Torr range. As in previous tests, a few drops of water were observed on the edge of the rotary joint housing at the beginning of the pumpdown. No emulsion was found on the inside of the joint housing.

B.4 CONCLUSIONS

The subject tests indicate that a Barco Type E Rotary Joint has a low enough leakage rate to be compatible with the Westinghouse lunar drill concept. Because of the low leakage rate observed with respect to the mass of the seal the formation of ice was not in evidence. More specifically, frosting did not occur because the total heat in the 2-ounce dynamic seal when stated at room temperature, more than overcame the heat loss due to a phase change occurring as the measured 0.8 grams per hour of water was lost. Once the seal began to turn, additional heat was generated by friction at the face of the seal. As was demonstrated in the third test described in this report, prior to startup, the seal can be kept at room temperature by means of a strip heater surrounding the joint housing.

The loss of water observed at the initiation of the pumpdown for each test may not have been leakage from the dynamic seal itself. Instead, while the joint was being filled with water and pressurized, a few drops of water may have adhered to the back side of the seal. With a reduction in pressure this water would leak out as was observed.

The presence of a graphite-water emulsion was observed only at the end of the preliminary test run. This effect would be expected since the self-seating carbon to steel dynamic seal must seat itself during its first few minutes of operation. The final seal is made when the carbon seal face wears until it makes full contact with the steel face. During tests of the rotary joint, the only wear noted on the dynamic seal was at the run-in period.

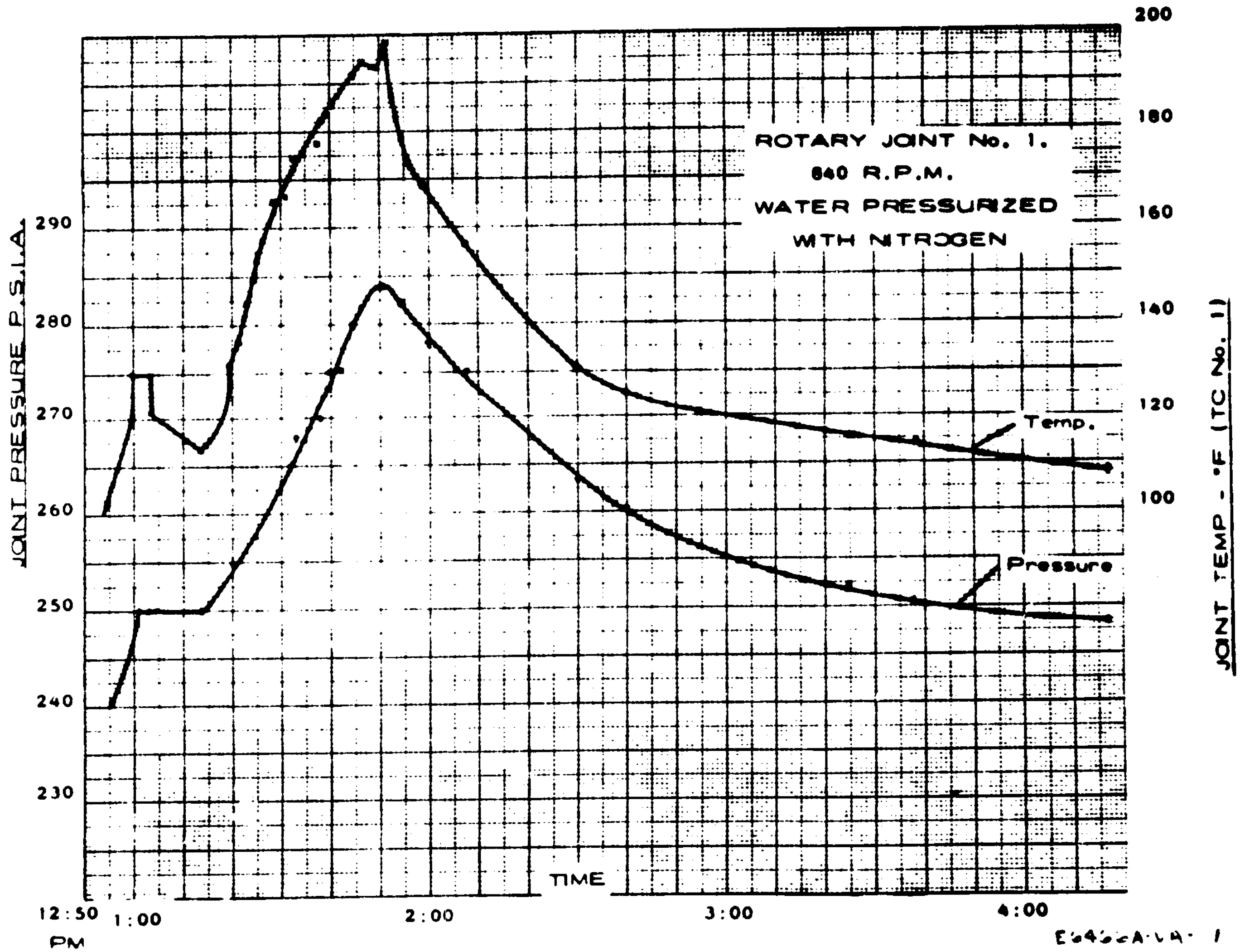


Figure Γ-2. Temperature and Pressure vs Time for Test at 1.6×10^{-4} Torr

The calculations below show that the water leaking from the joint could not freeze during the one hour operating period. The basic problem involved is to determine if the amount of heat present in the joint is sufficient to keep the water above the freezing temperature. Expressed in equation form:

$$W_s C_{ps} \Delta t_1 = W_w C_{pw} \Delta t_2$$

where:

W_s	=	weight of steel - 2 oz.
C_{ps}	=	specific heat of steel = 0.11 Btu/lb°f.
Δt_1	=	$T_s - T_o$
T_s	=	temperature of steel
T_o	=	equilibrium temperature of steel and water
W_w	=	weight of water = 0.8 gram for 1 hour
C_{pw}	=	specific heat of water = 1
Δt_2	=	$T_o - T_w$
T_w	=	temperature of water corresponding to vacuum temperature

These equations neglect the frictional heat of the rotating joint and hence, represent the worst case.

Six conditions were investigated which represent the beginning of each run (worst case so far as frost forming is concerned) and after the joint reached an equilibrium temperature in a vacuum of 0.3 Torr to 10^{-4} Torr the sample calculation for one condition is shown below and the resulting equilibrium temperature for the conditions considered is summarized in table B-1.

Sample calculaton: Joint at room temperature - 0.3 pressure

W_s	=	2 oz = 0.125 lb
T_s	=	70°F
W_w	=	0.8 gram = 1.764×10^{-3} lb
T_w	=	22°F (corresponds to 0.3 torr)

TABLE B-1

EQUILIBRIUM TEMPERATURE OF ROTARY JOINT AND WATER LEAKAGE AFTER 1 HOUR

Joint Temperature at Start of Run (°F)	Pressure (Torr)	Equilibrium Temperature After 1-Hour Running (°F)
70	0.3	+59.5
70	10-3	+50.1
70	10-4	+47.1
169	0.3	+147
169	10-3	+138
169	10-4	+135

$$0.125 \times 0.11\, \Delta t_1 = 1.76 \times 10^{-3} \times 1 \times \Delta t_2$$

$$0.013.75\, \Delta t_1 - 1.76 \times 10^{-3}\, \Delta t_2 = 0$$

$$\Delta t_1 + \Delta t_2 = 70 - (-22) = 92$$

$$1.76 \times 10^{-3}\, \Delta t_1 + 1.76 \times 10^{-3}\, \Delta t_2 = 1.62 \times 10^{-1}$$

$$15.51 \times 10^{-3}\, \Delta t_1 = 1.62 \times 10^{-1}$$

$$\Delta t_1 = 10.5$$

$$70 - T_0 = 10.5$$

$$T_0 = 59.5°F$$

Equilibrium temperature of water and joint is 59.5°F which is well above freezing.

B.5 ROTARY SEAL ACCEPTANCE TEST

B.5.1 Requirements

The references in paragraph 2.1.3b of the acceptance test agreement in this report proved to be incorrectly stated. These references should be Progress Report 4, Appendix C and Progress Report 8 paragraph 10.3.2., page 42. These changes were incorporated in the revised test procedure.

B.5.2 Revised Test Procedure

B.5.2.1 Purpose

The purpose of the test was to evaluate the performance of a test unit of the rotary joint for the lunar drill engineering model. The unit with the transformer in place will be run in a vacuum environment at an internal pressure and temperature commensurate to those parameters set forth for the engineering model thermal control system (1000 rpm, 15 psi).

B.5.2.2 Procedure

B.5.2.2.1 Static Leakage Test. - Fill rotary joint with water and pressurize unit with nitrogen to 15 psi above ambient (30 psia). Allow the unit to sit overnight while pressurized. If there is no drop in gauge pressure, proceed to vacuum testing. If an appreciable loss of pressure is evident, repressurize the rotary joint and determine the point or points at which leakage is occurring. Once the leakage has been corrected, the static test should be repeated.

B.5.2.2.2 Vacuum Leakage Test. - With the rotary joint filled with water (water level should be set above the pressure gage but below the pressurization valve) and sealed at 0 psig, the unit should be weighed to within 0.1 of a gram and mounted in vacuum chamber. A pumpdown to the 1×10^{-4} Torr range should then begin. During the pumpdown period, the quartz lamp mounted in the chamber is to be used to bring the test unit up to 212°F as measured by a thermocouple mounted on the rotary joint housing in close proximity to the dynamic seal.

Upon reaching a vacuum of 1×10^{-4} Torr and a rotary joint temperature of 212°F the drive motor should be turned on and the unit run for 30 hours at 1000 ±200 rpm. The temperature of the unit should be maintained at 212 to 250°F by intermittent operation of the quartz lamp. The operating temperature should not be allowed to exceed 250°F. If a shutdown of the heat lamp does not keep the test unit below maximum temperature, the drive motor is to be shut down until the temperature drops to 212°F.

Measurements to be made during the test and their corresponding data rates are as follows:

- Test chamber pressure - 4/hr
- Internal joint pressure - 4/hr
- Joint temperature - 1/min (TC recorder)
- Rotary joint weight - Before and after test

With the completion of 30 hours of running time in vacuum, the test unit is to be weighed to within 0.1 of a gram and the leakage rate in grams/hr calculated.

B.5.2.2.3 <u>Equipment Needed.</u>

a. Vacuum chamber (1×10^{-4} Torr capability)

b. Test unit of rotary joint containing transformer

c. Quartz lamps (at least 2) and reflectors

d. TC mounted on test unit

e. Nitrogen bottle

f. Drive motor (1000 ±200 rpm)

g. Pressure gage (0-50 psig) and associated piping

h. Breadboard thermistor bridge circuit

i. Breadboard signal conditioner

j. Recorder for TC and signal conditioner

Figure B-3 shows the test setup.

B.5.3 <u>Acceptance Test Results</u>

A preliminary static testing was performed for a continuous 72-hour period during which the gage pressure varied between 21-1/2 and 17-1/2 psia and 3 grams of water were lost. A second static test was performed in a total of 6-1/2 hours from the start of pumpdown. A malfunctioning thermocouple indicated lower than 200°F for the major portion of the test. However, seal gage pressure indications were interpreted to indicate that temperatures from 290°F to 307°F existed for the last 5 hours of the test. Pressures varied during this period from 58 to 6.74 psia. Five grams of water were lost.

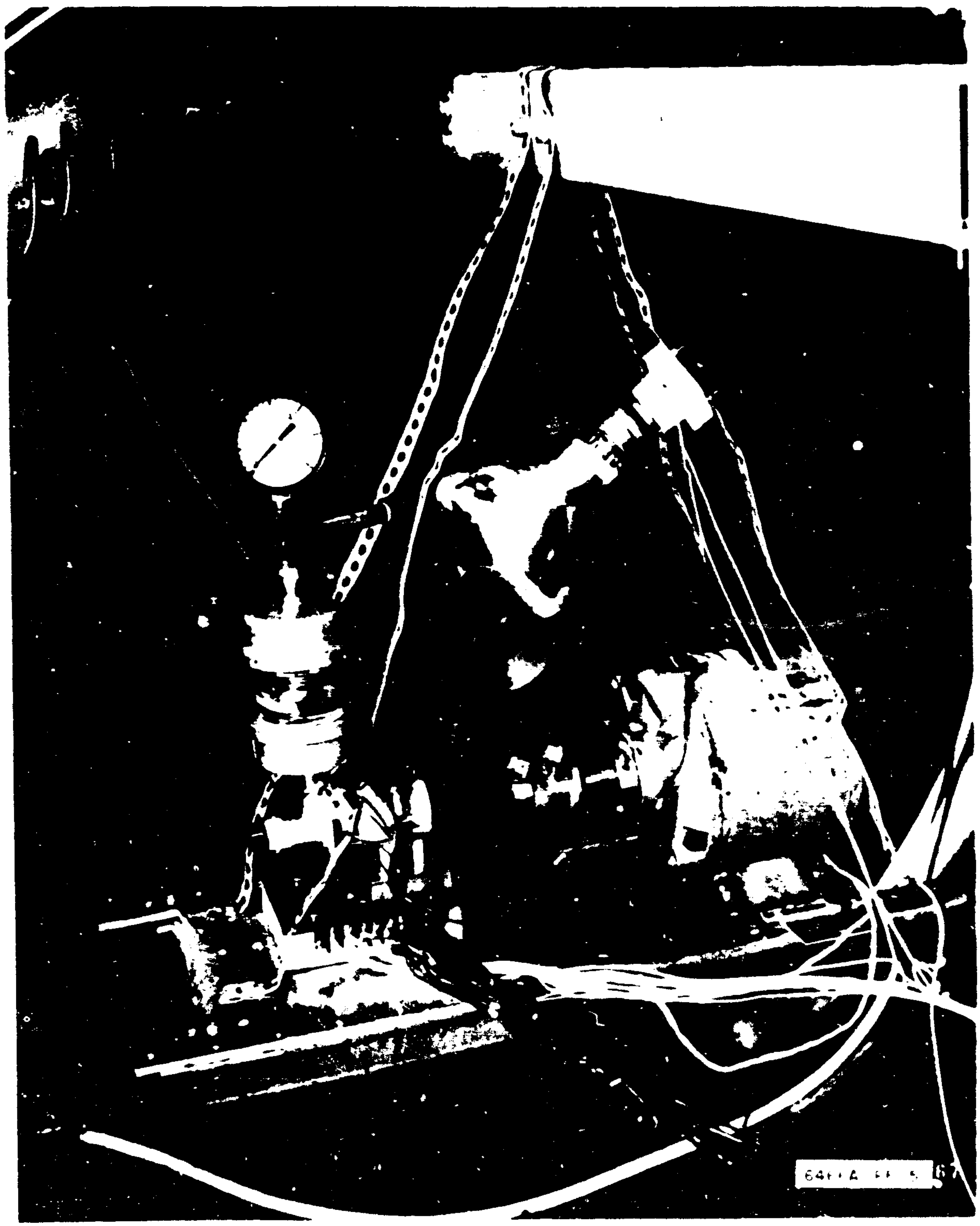


Figure B-3. Rotary Joint Vacuum Test Setup

After some preliminary checks and reweighing, the unit was rotated at 1000 rpm for approximately 8 hours in a 10^{-4} to 10^{-5} Torr vacuum. The water temperature remained at approximately 270°, and the seal pressure varied from 33 to almost 70 psia. When the pressure was released on the unit, an estimated 25 ml of water blew out. The total water loss, including that blown out, was 63 grams. The test was terminated due to the pressure being over 70 psia for a period 5 hours. It was found that the seal bellows had come loose permitting a loss of steam and enabling the bellows to rub against the bearing. The bearing retainer also was rubbing against an edge of the rotary joint cap. The frictional heat appeared to be the cause of the high temperatures and resultant high pressure.

The bellows was replaced, the joint cap edge was chamfered to relieve the rubbing on the bearing retainer, and the unit was cleaned and reassembled with the same seal.

B.5.3.1 Data

The final rotation test in a vacuum was run for a total of 25 hours. Figures B-4 and B-5 show the test data and figure B-6 shows the resultant curves.

Examination of the data from the subject test indicates the following:

a. Slight boil-off and leakage at 1430 to 1630 hours (2 hours of running after 2 hours static in vacuum).

b. Sharp rise of motor temperature at 1900 hours caused added boil-off and some leakage through the seal, lowering the joint pressure and dropping its temperature. This, in addition to motor outgassing, resulted in a short duration rise and fluctuation of chamber pressure.

The sharp rise of motor temperature was undoubtedly due to increased friction of the upper bearing retainer rubbing against the housing cap. This situation relieved itself in approximately 1/2 hours with temperatures and pressure falling accordingly.

TEST RECORD

Oct. 7-1966

K2109053

SUBJECT: LUNAR DRILL ROTARY JOINT

CUSTOMER:

S.O. OR TEST NO.:   S.O. OR L. SPEC. NO.:   DRAFT NO.:   SERIAL NO.:   FRAME NO.:

TO DETERMINE: Use of rotary joint in vacuum

The unit was weighed at [illegible] grams.
The thermocouples were attached as shown:
#1 Joint near seal. (Mylar tape)
#2 Chamber ambient. (Behind reservoir)
#3 Reservoir, in back (Mylar tape).
#4 Motor, top [illegible] (Mylar tape)
Then the unit was placed in the chamber. Ambient air in the unit reservoir was removed by heating the reservoir to [illegible] 156° F, [illegible] the [illegible] valve, removing the heat, and shutting the valve after the pressure had dropped [illegible] 2 [illegible] on the gage. The chamber was closed at 11 55 AM.
1.00 PM Vacuum Pumps Started.
Pressure = 7 [illegible]

Time		Vac.	Current	#1	#2	#3	#4	Valve	Motor	
1 15	PM	28	.40 a	214 F	192° F	210 F	109° F	134	OFF	
1.30		36	.60 a	222°	189°	216	111°	125	OFF	
1 45		41	.48 a	222	199°	221°	119°	112	OFF	
2:00		43	.38 a	219°	189°	221°	112°	110	OFF	[illegible]
2:15		44	.48 a	222°	196°	229°	118°	105	OFF	
2.30		46	.10 a	226	186°	226°	121	102	OFF	
2:45		46	[illegible]	228	188	221°	127	100	ON	
2 45								90	ON	
3.00		45	[illegible]	222°	182	215°	132	80	ON	
3:01								75		
3:15		44	[illegible]	222°	175	210	146	75	ON	change [illegible] 45
3:30		40	[illegible]	216	168	206	156	65	ON	
3:45		38	[illegible]	218	167	204	168	65	ON	changed [illegible] 60
4:00		36	[illegible]	215	164	197	174	60	ON	
4:30		36	[illegible]	216	164	195	192	60	ON	
7:30		26	[illegible]	188	165	188	220	60	ON	changed [illegible]

E6606A-JA-53

Figure B-4. Rotary Joint Data Sheet 1

TEST RECORD

Oct 7, 1966

K 2109954

SUBJECT: Lunar Drill Rotary Joint (Cont-II)

CUSTOMER:

S. O. OR TEST NO.:   E. OR L. SPEC. NO.:   SHAFT NO.:   SERIAL NO.:   FRAME NO.:

TC DETERMINING: Temperature

Time	Pressure Gage	Chamber	#1	#2	#3	#4	
5:30		3.9(10^{-5})			↑		
6:45		3.5(10^{-5})					
7:30		1.5 × – 2.5(10^{-4})					Burnout Illustrated [illegible] #1 [illegible]
7:40		5(10^{-4})					
8:45		5(10^{-4})			Recorder		
9:30	25	7(10^{-4})				chart	
[illegible]	[illegible]	[illegible]					
	[illegible]	[illegible]					
[illegible]	[illegible]	[illegible]					
[illegible]	[illegible]	[illegible]					
[illegible]	93	[illegible]					
[illegible]	97	3.0×10^{-5}					
0400	33	[illegible]					
0500	26	6.5×10^{-4}					
0600	18	8.5×10^{-5}					
0700	8	1.3×10^{-5}					
0800	7	8.3×10^{-6}	224	167	198	216	
0900	6	7.5×10^{-6}	226	166	197	217	
1000	5	7.2×10^{-6}	229	165	196	217	
1100	5	6.6×10^{-6}	222	165	196	217	
1200	4	6.2×10^{-6}	238	166	197	217	
1300	4	5.8×10^{-6}	219	166	196	218	

SHUT OFF VAP & PUMP

CHAMBER VENTED AND READY TO BE OPENED

THE UNIT WAS WEIGHED AT 3851 GRAMS AFTER THE TEST.

7:30 AM 10/10/66 No water remaining in unit

Loss = 14 grams

E6466A-VA-54

Figure B-5. Rotary Joint Data Sheet 2

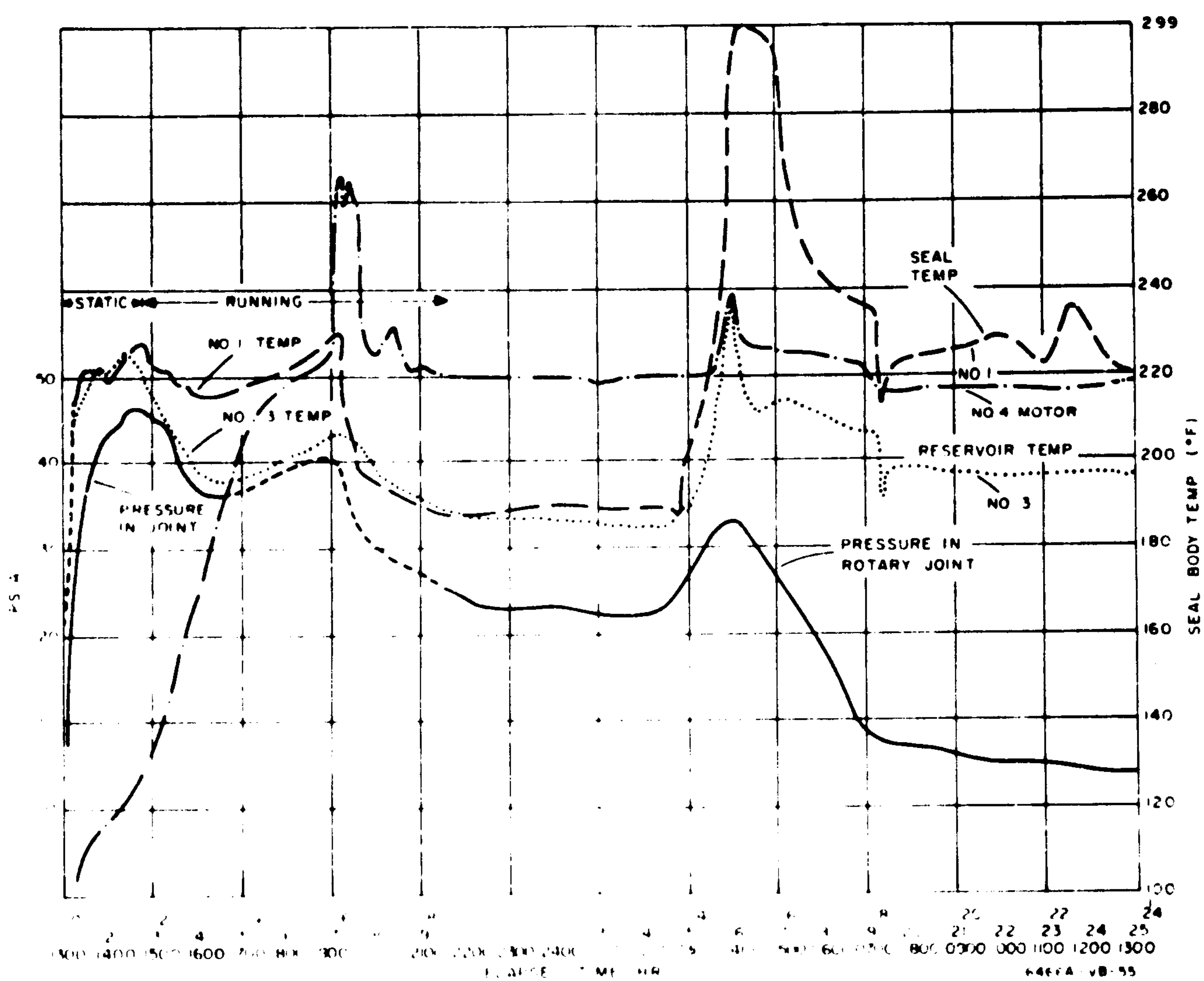


Figure B-6. Rotary Joint Vacuum Test Curves

c. System equilibrium was reached at 2000 hours and remained stable for approximately 7 hours, although at 0200 the chamber pressure fluctuated due possibly to a small outgassing burst from the motor.

d. At 0245 hours, th joint temperature and pressure and reservoir temperature began to rise steeply, followed 24 minutes later by a parallel but minor increase in motor temperature and corresponding rises in chamber temperature and pressure. These events all peaked at 0400 hours with joint temperature reaching 299°F and persisting for approximately an hour.

e. The motor and chamber temperatures and chamber pressure dropped to prepeak values immediately after the peak, indicating that a short leakage or outgassing burst had accompanied the sudden rise in joint temperature. An increase in seal face pressure occurred due to the seal retainer being forced out of its seat in the housing cap. This, together with chips from the bearing retainer binding the bearing would cause a large increase in joint-temperature with only a small rise in motor load. The high joint temperature could have been sufficient to allow the inner race of the seized bearing to turn on the spindle relieving the motor load, but wearing the spindle, and after a few minutes becoming free enough to reduce the friction and associated housing temperature.

f. At 0700 hours the joint pressure had dropped below the initial value and since the joint temperature was still over 230°F, the indication is that most of the water had been lost at this point.

g. During the remaining 6 hours, jo nt pressure remained low and several fluctuations of joint temperature indicated a small amount of water was intermittently being boiled off.

h. The system was dry at the conclusion of the test.

B.5.3.2 Summary

a. The rotary joint seal test running under vacuum conditions indicated an overall leakage rate of approximately 8 grams per hour, the major portion of which occurred after 15 hours of operation.

b. Mechanical design faults of parts other than the face seal which appeared to be reusable, were undoubtedly the cause of most of the leakage.

(1) The bearing appeared to be bound by solid lubricant chips from the retainer. The chamfer on the rotary joint cap is not sufficient to prevent rubbing.

(2) The bellows came loose from the cap.

6466A

APPENDIX C

THERMAL ANALYSIS OF A LUNAR ROTARY CORE DRILL SYSTEM

Prepared for

WESTINGHOUSE ELECTRIC CORPORATION
Defense and Space Center
Baltimore, Maryland

by

Arthur D. Little, Inc.
Cambridge, Massachusetts

Under

Purchase Order 02TJ 89 24179-0S

24 January 1966

67716

FOREWORD

The thermal analyses of the lunar core drill system described in this report were undertaken under subcontract to Westinghouse Electric Corporation, Space and Defense Center, Baltimore, Maryland. Because these analyses were in support of the developmental phase of the lunar drill, simplifications and approximations have been made to permit evaluation of the most critical parameters affecting drill system performance within the limited scope of this study. Detailed thermal analyses of the drill system can be carried out when the operating parameters, data on drilling mechanisms and the design of the cooling system are more closely specified.

The authors express their appreciation to Mr. G. Woo, Mr. R. Phillips, and Dr. J. W. Wild of Westinghouse for their assistance in this program.

I. SUMMARY

This report summarizes the work accomplished during the period from September 24, 1965 to January 24, 1966 on the thermal analysis of the lunar drill system according to the statement of work entitled "Lunar Drill System-Thermal Analysis" revised and dated August 17, 1965.

A. PURPOSE

The primary objectives of the thermal analysis program were to:

(1) develop a thorough understanding of the heat transfer in the cutting zone during the core drilling operation in the lunar environment.

(2) examine analytically the effects of such parameters as drilling rate, rotational speed, rock properties, drill type and size on the temperature distribution within the drill bit, rock formation and the core sample.

(3) establish the relationships between the heat flow in the matrix and the temperature distribution near the cooling zone of the drill.

(4) establish the factors affecting drill performance such as outgassing and chemical reactions.

B. SCOPE

To meet the objectives of the program we summarized the available evidence on:

(1) the lunar environment which may control the drill performance.

(2) the effects of heat generated by drilling on the core integrity.

(3) drill system operating parameters and drill system thermal parameters such as the thermal properties of the drill construction materials, the diamonds, the matrix materials and the rock surrounding the drill.

The different design concepts for the lunar drill systems served as a basis for the thermal analyses of the drill system. Results of analytical procedures based on simplifying assumptions were compared with computer calculations to establish validity of the analyses and to investigate the thermal behavior of the drill system.

C. SIGNIFICANCE OF THE PROGRAM

The significant results of this program include: the development of analytical procedures for obtaining temperatures in the drill bit, evaluation of the cooling requirements for the drill, the mechanism of heat exchange between the drill shaft and the surrounding rock, and the heat transfer between the chips and the diamonds.

D. PROGRAM RESULTS

(1) The diamond and matrix temperatures can be maintained below the maximum allowable operating temperature by an efficient cooling system.

(2) Eighty to ninety percent of the energy released at the drill face is carried away by the chips.

(3) The design of the cooling system must achieve heat transfer coefficients high enough to prevent burnout. These coefficients should be above 50 Btu/hr ft^2 ^{o}F.

(4) Core thermal degradation can be restricted to a thin outer layer of the order of 0.1 inch.

(5) The temperature of the rock surrounding the drill decreases very rapidly to ambient values within a distance of about 0.2 inch in both the axial and radial directions.

(6) Experimental data is essential to define drill system operating parameters, to confirm the assumptions made and to verify the results of these analyses.

II. INTRODUCTION

In the studies of the lunar surface materials, the most important questions arising will be the relevance of the data obtained to the history of the moon. Questions concerning the bulk chemical composition, particle sizes of loose surface material and bearing strength can be answered by surface observations. Although knowledge of the bulk composition, particle size, etc., is necessary, subsurface sampling must be done to answer the most important questions. To get the most information from a drill hole, a core must be taken, for from the core we can determine the sequence, if any, of deposition or formation of the near surface materials. Because the core sample is oriented, fracture and flow patterns can be related to large surface features. Petrofabric studies (in solid rock materials) will yield information on the movement and orientation of minerals which indicates the stresses present during and after formation of the deposit. These advantages along with the obvious advantage of detailed petrologic and chemical analyses make a core sample indispensible in the preliminary subsurface investigation.

However, the heat generated by drilling may be a problem especially if certain minerals are present on the moon subsurface. Phyllosilicates, such as clays, mica, and serpentine, have hydroxylated water and the removal of this water is encountered by heating. The amount of water present varies almost inversely with its ease of removal. For instance, serpentine which may contain up to 13% by weight of water as (OH) starts to loose some of this water around 200°C while muscovite, biotite, and phlogopite mica decompose at about 500°C, 650°C and 1000°C respectively.

Silicate minerals of the amphibole series will also lose hydroxylated water at temperatures ranging [illegible] $^\circ C$ to $1000^\circ C$. The amphiboles and micas are products of igneous activity on the earth, where as the clays and possibly serpentine are products of alteration by hydration of pre-existing rocks. Therefore, the existence of the micas and amphibole seem more probable on the moon, since hydration processes are absent there. When hydrated minerals are heated, the temperature of dehydration is usually high enough to not only remove the water but to synthesize new stable phases. For instance, serpentine alters to forsterite + SiO_2 + H_2O. Mica alters to feldspar + pyroxene + H_2O. Although the petrographer should be able to determine the original phases present, knowledge of the temperatures to which the minerals have been exposed is obviously necessary in order to know what the possible alteration reactions could be. Thus, predictions of the temperatures of the core are necessary to assess the possible core degradation. Thermal analyses are required so that the appropriate design of the cooling system for the drill can be selected. Such analyses can provide an insight into the drill operating conditions in the lunar subsurface environment, the temperature distribution in the surrounding rock and the core, and guide the design of the drill bit and chip removal techniques.

In the following sections the drill system which was analyzed is described, the parameters used in the thermal analyses are discussed, and the approaches and results obtained in the thermal analysis of the drill system are given.

III. DESCRIPTION OF DRILL SYSTEM

A. GENERAL DESCRIPTION

The diamond core drill proposed for use in obtaining lunar rock samples will utilize a wire line core barrel. Core drills used for geological explorations have evolved from a single drill tube string to the wire line core barrel (Longyear, 1965). A separate inner concentric tube, the core barrel, is lifted out of the hole with a wire line or cable. Because this operation is faster and requires less manipulation than pulling and disassembling the drill string, the wire line method is particularly applicable to use on the moon. When the drill bit is to be used to drill several core lengths before replacement is required, the wire line core barrel system speeds up the drilling-core retrieval-resume drilling cycle.

A major design modification is required for lunar use because drilling must be done "dry". In earth-rock drilling, water is pumped down the inside of the drill string to serve three purposes--(1) the drill-rock working interface is cooled, (2) rock chips are flushed away from the working face and removed, and (3) lubrication is provided between the drill string, rock, and core.

Dry drilling is required on the moon because of the large weight penalty accompanying water transport and the difficulty of recirculating a cooling fluid in an open system without major losses. A closed cooling system must be used on the moon to conserve water.

Chips must be transported from the drilling face and collected. Chips will be carried upward outside of the drill barrel by a set of spiral auger flutes and transferred into and collected in a "chip basket" above the core.

Mechanical rotary power is transmitted to the drill by the hollow drill shaft from an electric motor drive on the surface. Cooling water flows down to the drill bit by gravity, cools the drill face and shaft by convection and vaporization, and returns as steam to a radiation-cooled condenser on the surface.

Current system design parameters call for a maximum electrical input of 3 kw. A 400 pound thrust load on the drill bit will be used to permit drilling at a rate of 1.2 to 2.4 inches per minute at 500-1000 rpm. The water cooling system is designed to operate at 390°F, 220 psia. These conditions are based upon preliminary estimates during the pre-proposal studies (ADL, 1965).

B. DRILL BIT DESCRIPTION

A detailed drawing giving the dimensions at the cutting end of the drill are shown in Figure 1. This figure was drawn from a partial print provided by Westinghouse and represents the drill design concept as of December 1965. Nominal dimensions are: hole diameter--2 inches and core diameter--1 3/8 inches.

The kerf (rock annulus ground away) is 5/16 inch wide. Three concentric tubes are contained in this space--the core barrel and the inner and outer tubes which form the hollow drill. Minimum practical radial clearances are provided between the rock, drill shaft, core barrel, and core. An annular width of 0.076 inch is provided for the cooling system in the drill.

The core barrel terminates in a set of loose, but captive, fingers and a taper seat. When the core barrel is lifted, the fingers wedge between

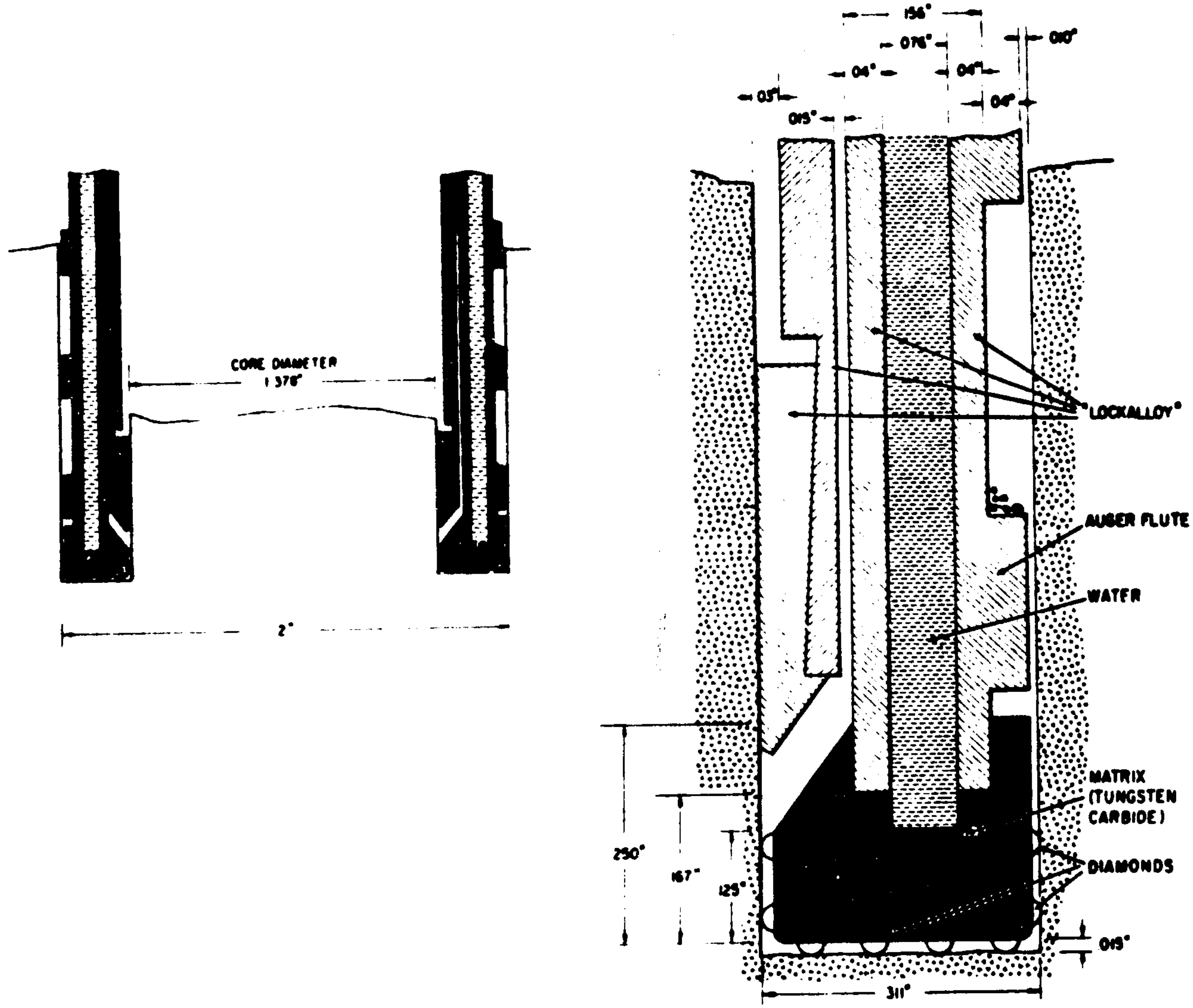


FIGURE 1 LUNAR CORE DRILL

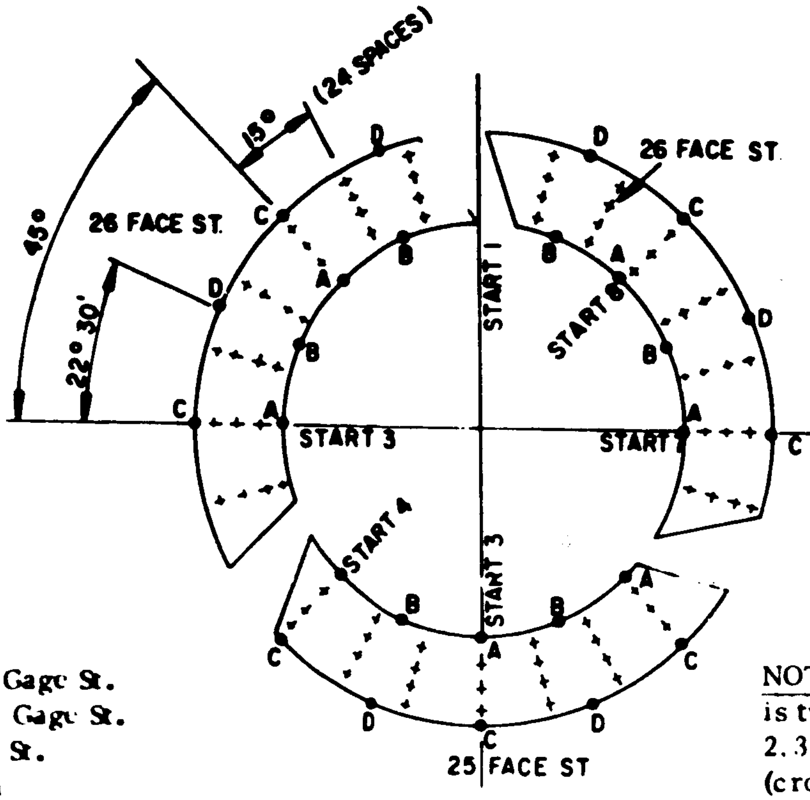
the seat and the core thus lifting the core. The wire line, core barrel, and grip fingers are strong enough to break the core from the rock mass.

C. DIAMONDS AND DIAMOND-SETTING MATRIX

A typical arrangement of the diamonds is shown in Figure 2. This is a reproduction of Figure B-3 from the Westinghouse Lunar Drill program progress report for October 1965. This spiral surface set bit design was selected by Westinghouse for further development based on dry-drilling tests conducted during October.

A total of 103 diamonds approximately 0.030-inch in diameter are used per bit. Of these, 78 are face stones which remove the major share of the rock. The o.d. and i.d. gauge stones ream and smooth the bore-hole and core to size for proper clearance with upper parts of the assembly. Twenty-one radial rows of three or four diamonds each contain the face diamonds. From row to row, the diamonds are spaced radially in an outward spiral so that each diamond tracks outside of the preceding one. The cutting chips are carried outward by the spiral pattern in a snowplow effect and are forced from the drill face by centrifugal force.

Powder metallurgy pressing and sintering methods are used to set the diamonds in a tungsten carbide-based matrix. Other components typical of matrix materials are titanium carbide, titanium, and cobalt. These matrix materials provide a hard, wear-resistant setting. The thermal expansion coefficients of the matrix and diamonds are close enough that a tight bond and good thermal contact are maintained at elevated temperatures. Three backward-slanting grooves are cast in the matrix face to aid radial transport of the chips.



Stone Placement

RAD	ANG
I.D. GA.	0°
.710	15°
.733	30°
.756	45°
.788	60°
.821	75°
.853	90°
.884	105°
.916	120°
.948	135°
.968	150°
.985	165°
O.D. GA.	180°

12 I.D. Gage St.
13 O.D. Gage St.
78 Face St.
103 Total

NOTE: This spiral sched. is typical for 8 starts. (1. 2.3.4...). Diamonds (crosses) follow spirals. Spiral marks represent every diamond (+) along the line.

FIGURE 2 ARRANGEMENT OF DIAMONDS IN DRILL BIT

D. CHIP TRANSPORT AND COLLECTION

The radial force or acceleration field will aid removing the chips from the cutting face and force the chips to move up the auger flutes. Chips may bounce between the stationary rock wall and the drill and auger rather than to settle and fill the auger. Two modes of chip flow in the annular space between the drill shaft and the uncut rock will be considered later in this report: (1) a "slug flow" in which the chips are displaced upward as a continuous mass and (2) a motion in which the chips follow a "spiral" movement along the auger flutes with much higher axial velocity than in case (1).

IV. THERMAL ANALYSIS PARAMETERS

A. DRILL SYSTEM OPERATING PARAMETERS

Listed below are system parameters that were used for the thermal analyses discussed in the following sections of this report:

(1) Maximum electrical power input to drill system, 3 kilowatts.

(2) Coolant water temperature, 390°F.

(3) Drilling rate, 1.2 in/min and 2.4 in/min.

The above parameters were specified by Westinghouse or accepted as "ground rules" agreed on by Westinghouse and ADL. Over-all NASA mission system considerations have established the drill system power as a definite limit. The coolant water heat-dissipation system will also have a design capacity of 3 kw. Cooling system temperature is not as rigidly fixed, but will not be changed unless important improvements can be demonstrated. Higher or lower drilling rates may be used depending upon the type of rock encountered, and the environmental conditions encountered.

The magnitude of the division of heat between the chips, rock and drill was one of the objectives of our calculations. We have analyzed the drill system based upon a variable distribution of energy flowing into the chips and rock and into the drill cooling system. The maximum chip temperatures will occur when all of the energy dissipated in the cutting zone goes into the rock and chips. The maximum diamond and matrix temperatures will depend on the chip temperatures, the heat transfer coefficients in the cooling system, and the heat transfer mechanism at the chip-diamond interface.

B. DRILL SYSTEM THERMAL PARAMETERS

In addition to the drill operating parameters, the thermal properties of the drill construction materials, the diamonds, the matrix materials, and the rock surrounding the drill must be established.

1. Drill Construction Materials

For steady state operation of the drill system, the only important parameter of the drill material required in the thermal analysis is the thermal conductivity. The thermal conductivity of the Lockalloy, the proposed drill construction material, was taken as 2.05 watts/cm^{o}C. This value was supplied by Westinghouse and is consistent with manufacturer's data and data available in the literature. This value is high compared to many metals; however, because the Lockalloy is a beryllium alloy, and beryllium itself has a high thermal conductivity, this value is not unexpected.

2. Diamonds

At room temperatures, diamonds have the highest thermal conductivity of all readily available materials. The thermal conductivity is dependent upon the type of the diamond, the purity, size, etc. Water-white diamonds are divided into types I and II, depending upon the wave length at which ultraviolet absorption occurs. Type II diamonds are subdivided into two kinds: Type II-a which refers to the electrical insulating kind, and Type II-b which are good conductors of electricity. The thermal conductivity of diamonds have been measured in the temperature range from liquid helium temperatures to above 300^{o}K by Berman, et al. (Berman, 1956). Typical values at room temperature vary from 10 to 25 watts/cm^{o}C, depending upon the type of diamond. Type II-a have the highest thermal conductivity values. The thermal conductivity of diamonds generally decreases in the temperature range from 200 to 300°K (in agreement with the theory of thermal conductivity fc i-conductors) and is expected to increase at temperatures above 500°K because of the importance of thermal radiation. In any case, the thermal conductivity of the diamonds is very high, compared to the other materials in the system. For calculational purposes, we have assumed the diamonds have an infinite thermal conductivity; i.e., we have assumed that there are no temperature gradients in the diamonds.

3. Matrix Materials

Thermal conductivity values of tungsten carbide matrix materials are shown in the following table for several matrix compositions (Loewen, 1956). Grade CA-4 and K-6 are cast-iron grades containing only WC and a small amount of cobalt binder. Grades CA-2 and K2-S are steel cutting grades containing TiC, Ti, and more cobalt than CA-4 and K-6. In the subsequent analysis, we have chosen a value of 0.50 watts/cm°C for the thermal conductivity of the more wear resistant grades of matrix material, the type that would most likely be used in the lunar thermal drill.

Thermal Conductivity of Matrix Material

Material Designation	Thermal Conductivity (watts/cm°C)			
	(200°F)	(500°F)	(700°F)	(1000°F)
CA-4	1.11	.95	.88	.81
K-6	.85	.74	.71	.68
CA-2	.52	.50	.49	.45
K2-S	.48	.49	.49	.49

4. <u>Lunar Materials</u>

The density, specific heat and thermal conductivity of the rock being drilled are important parameters in the thermal analysis of the operation of the lunar drill. Figure 3 shows typical density values for a wide variety of terrestrial rocks. (Numbers on Figures 3 to 6 refer to references given in Appendix B.) Included in the figure are several values for vesicular and powdered rocks, which show the largest variation in density and the lowest absolute values. In the computer analysis described in this report, we have chosen a value of 2.8 gm/cm^3 as representative of a typical dense solid rock.

Figure 4 shows the specific heat of various rocks. The data presented are for temperatures at or near room temperature. The variation in specific heat of most rocks is small; rocks with a high moisture content have a high specific heat because of the high specific heat of water compared to silicates. The specific heat of most minerals increases with temperature because of increased vibrations of the atoms about their lattice positions. Increases of about 50% over the temperature range from 0 to 800°C are not uncommon. In subsequent calculations, we have chosen a value of 0.24 cal/gm°C (1.0 joules/gm°C) as representative of the specific heat of a solid rock at the slightly elevated temperatures produced by drilling.

Figure 5 shows the thermal conductivity of rocks according to their type. The data in this figure are given for temperatures at or near room temperature. The thermal conductivity of solid rocks depends upon the mineralogical composition, the orientation of the crystals throughout the structure, the degree and size of the microcracks and fractures in the rock, and the temperature. As a result of this dependence on a large

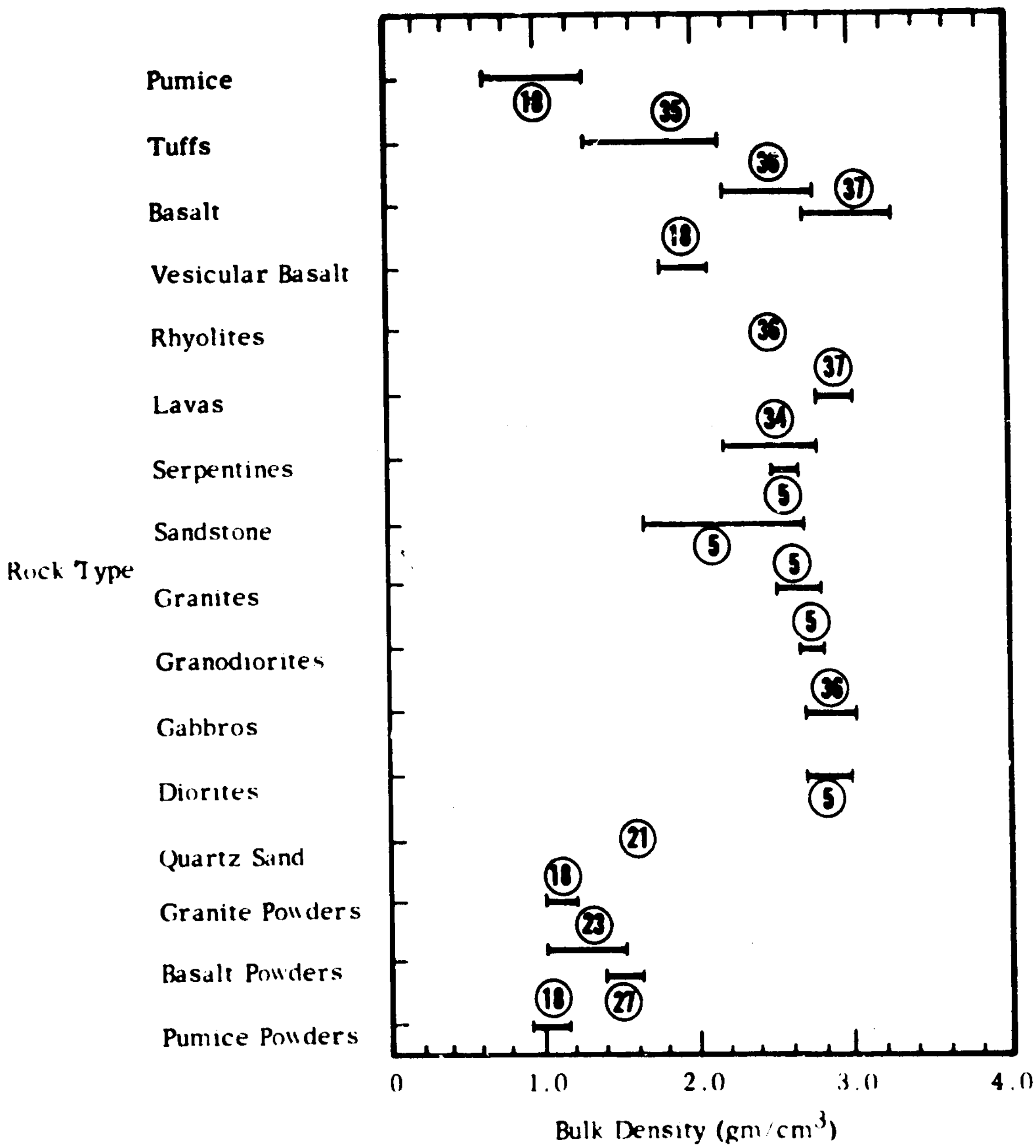


FIGURE 3 BULK DENSITIES OF SELECTED ROCKS AND ROCK POWDERS

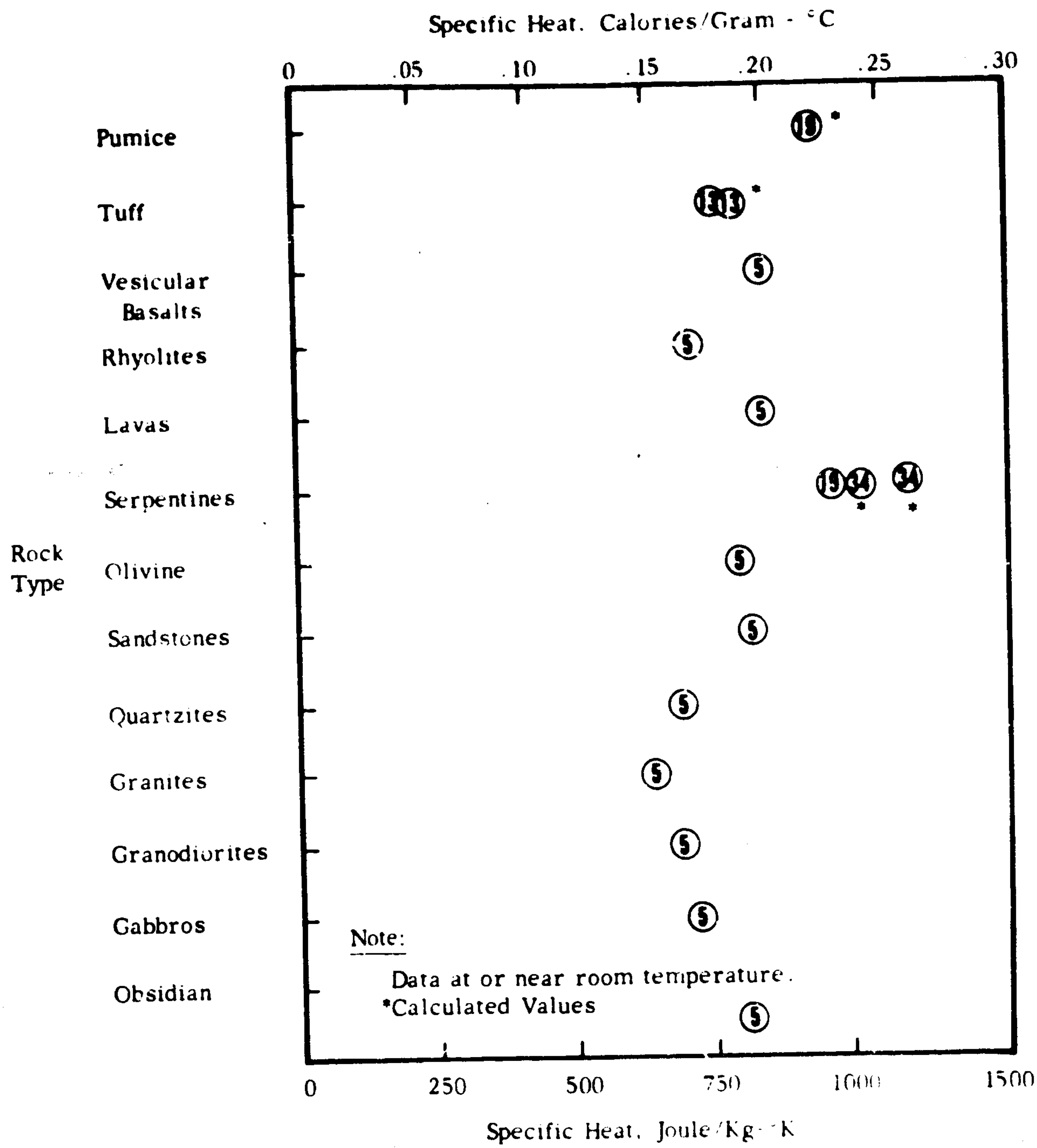


FIGURE 4 SPECIFIC HEAT OF SELECTED ROCKS

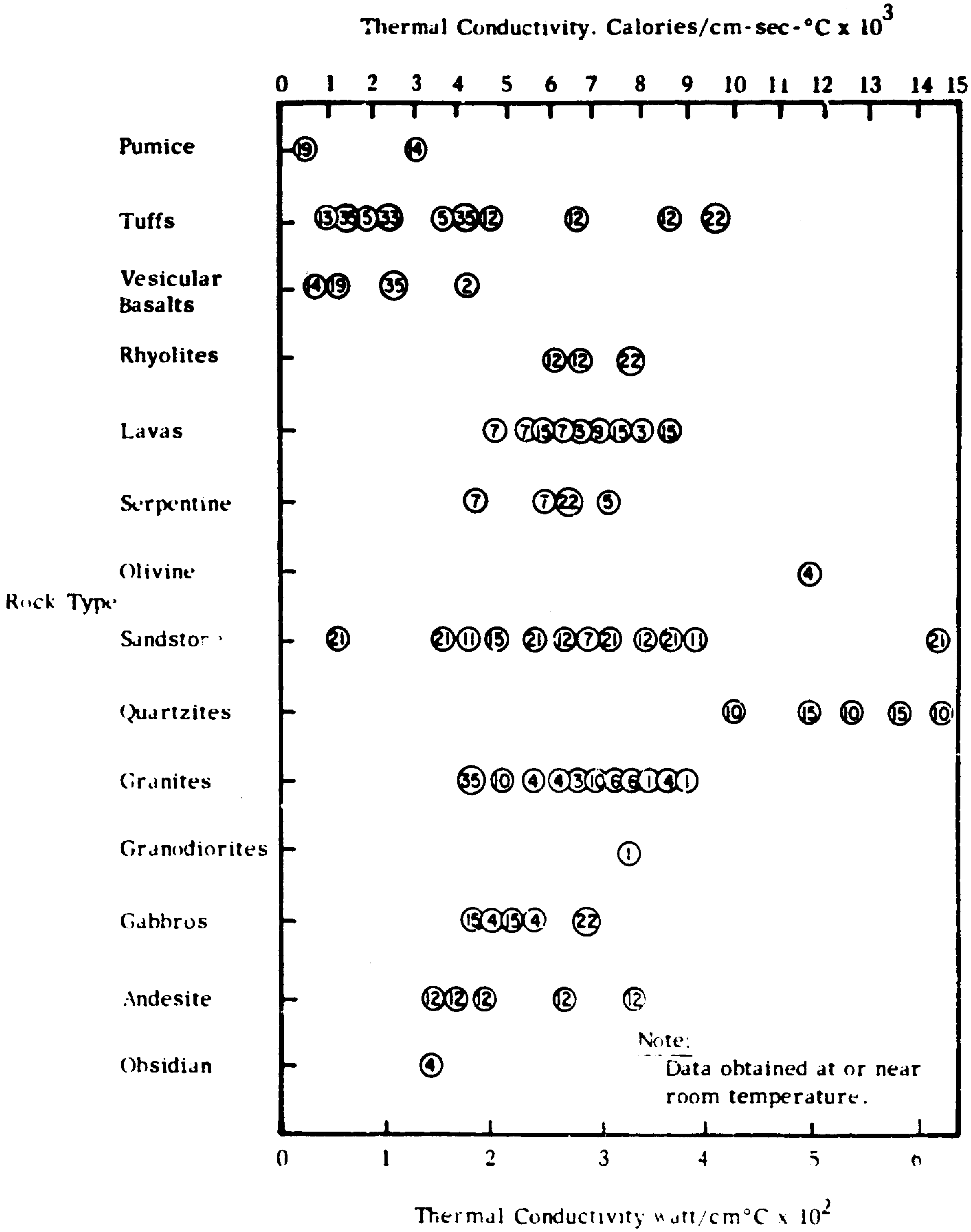


FIGURE 5 THERMAL CONDUCTIVITY OF SELECTED ROCKS

number of variables, there is considerable variation in the thermal conductivity. The figure shows that the variation in any particular type of rock is almost as large as the variation over a wide range of rock types. The effect of temperature on thermal conductivity of solid rocks depends upon the type of rock and the temperature level. Figure 6 shows the temperature dependence of thermal conductivity for several types of rocks. Rocks which are of a glassy nature generally show a strong increase in thermal conductivity with increasing temperature. Other rocks which seem to show an increase in conductivity with temperature are anorthosite and some gabbros. Most granites, limestones, slates, etc., show a decrease in thermal conductivity with increasing temperature. The more porous the rock, the greater the trend to increasing thermal conductivity with increasing temperature. This is probably due to the increased importance of thermal radiation at high temperatures. In the computer calculations, we have assumed a value of 2.5×10^{-2} watt/cm^{o}C for the thermal conductivity of a typical rock. This would correspond to a rock similar to granite or basalt. Other values of rock properties may be used in the parametric analysis presented in this report to determine their effects on drill and rock temperatures.

Another variable which enters in the analysis is the thermal diffusivity of the rock. Thermal diffusivity is the ratio of thermal conductivity to volume specific heat or (conductivity/density x specific heat). Values of the thermal diffusivity may be computed from the values of the individual parameters given above. The variation in the thermal diffusivity among rock types is due mainly to the variation of thermal conductivities. Because there is the general trend of increasing thermal conductivity with

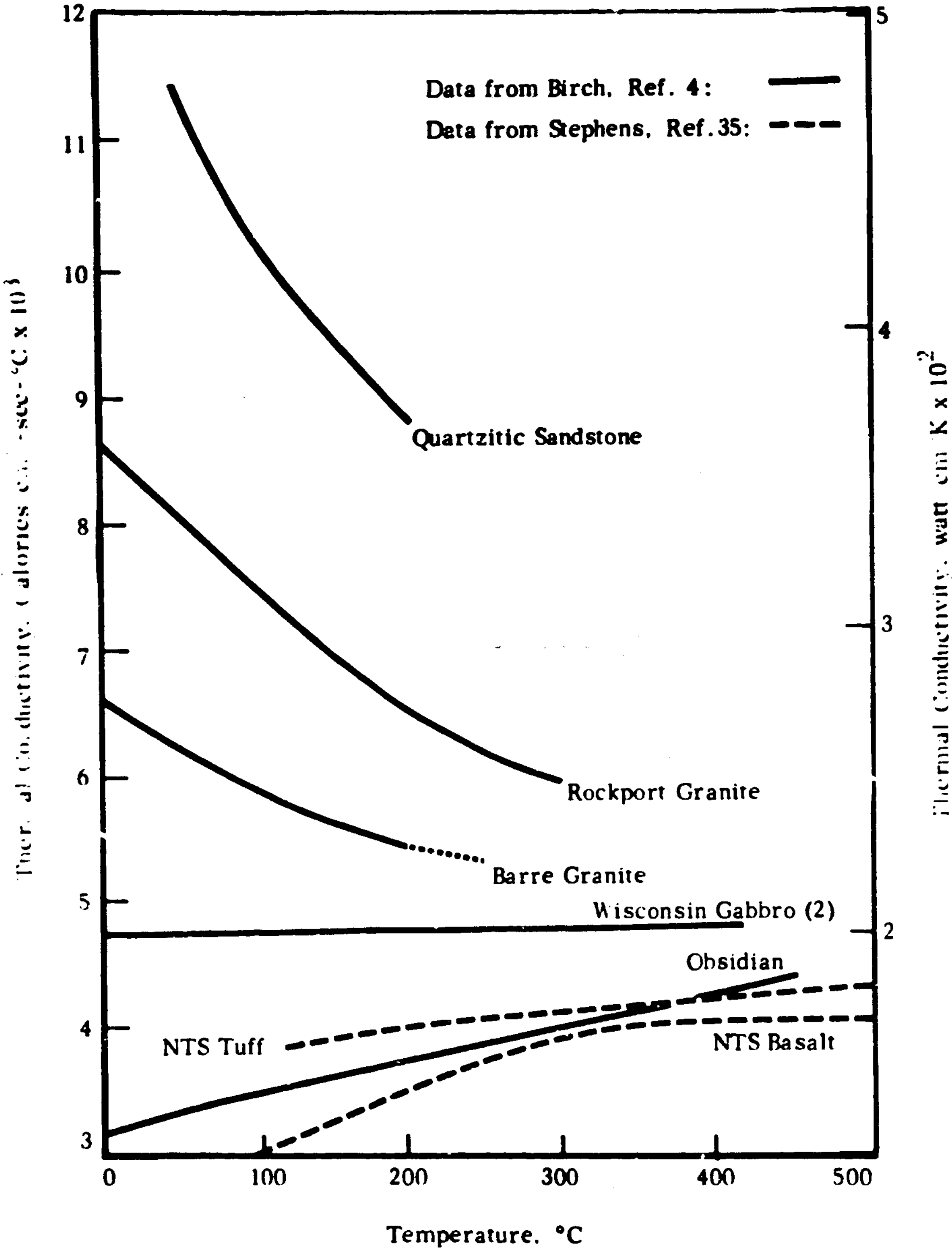


FIGURE 6 EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY OF SELECTED ROCKS

increasing density, the over-all variation in the thermal diffusivity of rocks is not as great as the variation in the thermal conductivity. In the computer calculations, we have used a value of 8.9×10^{-3} cm^2/sec for the thermal diffusivity of a typical rock.

V. THERMAL ANALYSES OF THE DRILL SYSTEM

A. ROCK AND CHIP TEMPERATURES

1. Introduction

In this section of the report the following three problems are considered:

a. The temperature of the chips at the front of the drill,

b. The temperature of the chips as they travel up to the chip basket and the amount of lateral heating of the drill shaft by the chips,

c. the degradation of the core by the heat flow and subsequent temperature rise of the rock.

Two procedures were used in the analysis--a computer program, and an approximate analytical method. In the computer program, the above three problems are solved simultaneously. In the analytical method, the problems are simplified considerably and solved independently. The results obtained with the computer program have established the validity and accuracy of the analytical method.

In the following sections the results of the two methods are presented. The parametric curves include solutions for a wide range of the operating parameters such as drilling rate and input power. Examples are given to demonstrate the use of the analyses.

Input power (W_2) represents that part of the total heat produced by drilling which heats the rock and that part carried away by the hot chips. The remainder of the total heat input (W_1) is transferred from the front of the drill through the matrix to the cooling system. W_2 is equal to the total heat produced by drilling only when there is no cooling at the front of the drill, i.e., $W_1 = 0$.

2. Computer Program Calculations

a. The Model

Our calculations are based on the model shown in Figure 7, which will hereafter be called the system. The system consists of the surrounding rock, the core and the chips up to the chip basket. The drill shaft is excluded in this portion of the analysis because its high thermal conductivity and the effect of coolant flow will maintain its temperature at 470°K (about 390°F), i.e., the temperature of the cooling fluid. A detailed and more accurate analysis of the drill shaft will not affect the solution of the problems considered here. Heat flow in the drill shaft near the bit is considered in Section V-B. For similar reasons, the core barrel was included in the system initially but has been excluded in the final analysis.

The system has cylindrical symmetry about its axis, and all dependent variables will be functions of the radial and axial coordinates only, i.e., there are no azimuthal variations. In a coordinate system fixed with respect to the drill (but not rotating with it), the surrounding rock and the core are moving past the drill with a velocity equal to the drilling rate U. The chips are also moving along the drill shaft towards the chip basket, with a velocity which can be found from conservation of mass considerations based upon the mechanism of chip motion assumed.

For a unique and determinate solution by any numerical method, the system must be completely enclosed by a surface of finite dimensions.

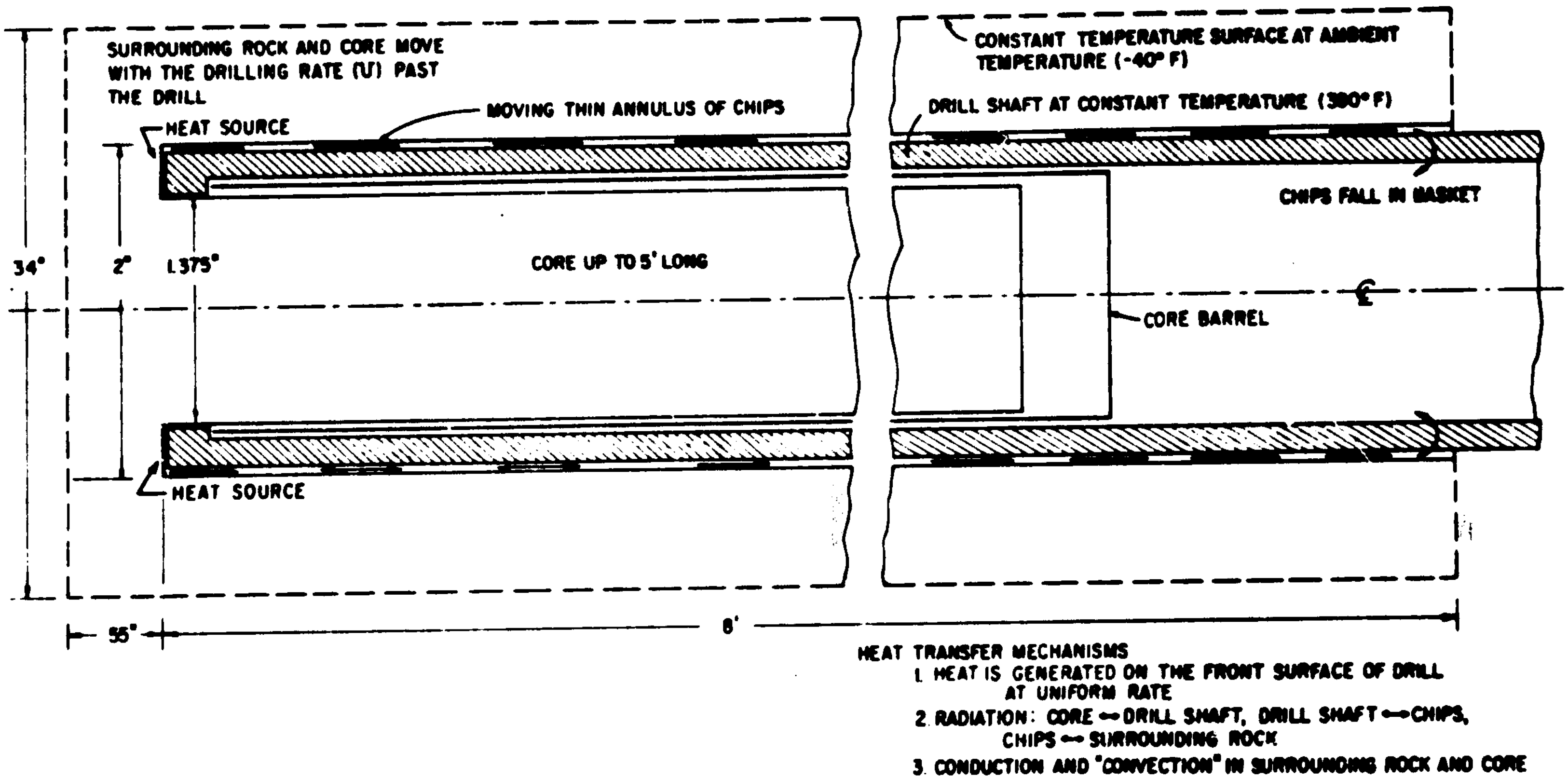


FIGURE 7 MODEL FOR THERMAL ANALYSIS OF LUNAR DRILL

Furthermore, since we are dealing with a system of heat conduction and radiation, the temperature or the heat flux on every section of the enclosure must be specified. The enclosure of our system consists of the following parts:

(1) A surface (the dashed line) outside of which the rock is not affected by the heat generated by drilling and remains at ambient temperature. The boundary condition for this surface is that the temperature is constant and equal to the ambient temperature of 230°K.

(2) The outside surface of the drill shaft, which is assumed to be at constant temperature equal to 470°K (see above).

(3) The zig-zag line in front of the drill, which represents a uniform plane heat source. The strength of this heat source is equal to W_2. Thus, the heat flux on this surface is specified. As the rock moves through this heat source, it is converted to chips which temporarily leave the system. They re-enter the system at the annulus (where they are picked up by the auger flutes) and travel towards the chip basket. A part of the energy from the heat source goes to the chips, the remainder flows into the rock. The heat source, the rock (just before it is converted to chips) and the produced chips are assumed to be at the same temperature. This temperature is a function of the radial distance from the axis. When the chips re-enter the system at the beginning of the auger, they are assumed to be well mixed and at an average temperature (averaged over the surface of the heat source).

(4) The small annular interior surface of the drill bit and the interior surface of the core barrel. These two surfaces enclose the core and are taken as one surface at a constant temperature equal to 470°K.

The heat transfer mechanisms in the medium representing the surrounding rock and core are not only solid conduction but also "convection," because the medium is moving. The surface of the core exchanges radiant heat with a surface at 470°K.

The exact mode of motion of the chips towards the chip basket and the resulting heat transfer mechanism with the drill shaft and the surrounding rock has not yet been specified. We have assumed that the chips move upward with a tumbling and turbulent motion, in a completely filled annulus (slug flow). The chips exchange radiant heat with the surrounding rock and drill shaft (the drill shaft is at 470°K). For these conditions maximum cooling of the chips and, therefore, maximum heating of the drill shaft will occur. Alternatively, we considered a chip movement where the bulk flow of chips has a spiral motion up the auger, while the motion of the individual chips which only partially fill the auger flutes is tumbling and highly turbulent. Radiative heat exchange will occur in this case also, however, the resulting cooling of the chips is very gradual.

b. Description of the Computer Program

We have used our computer program to solve steady state heat transfer in the system by the "Method of Zones," (Strong & Emslie, 1955).

In the method of zones, it is assumed that within a chosen volume element the temperature distribution is parabolic in the various space coordinates. For this temperature variation, formulae are derived for the average temperatures of the volume element and its surfaces. The heat balance equation for the volume element is a linear algebraic equation involving these average temperatures. The coefficients of the temperatures are appropriate conductances. If there is a volume input power, an appropriate input power term is added to the heat balance equation. Similar heat balance equations are written for each surface of the volume element. However, when radiation is involved, the surface heat balance equations involve the fourth power of temperature.

In the method of zones, a given system is divided into zones and appropriate heat balance equations are written. These equations are solved simultaneously by our computer program. However, all conductances, view areas, input powers and other information must first be calculated and supplied to the program as input data in the form of an input tape. For a large system, such as the drill system considered here, producing this input tape is a tedious and lengthy task, and even with the help of calculators, this may take several man-weeks. In addition, each time a single parameter of the system is changed (e.g., rock conductivity, drilling rate, size of zones, etc.), a completely new tape must be produced. Therefore, we devised another computer program to produce an input tape in less than one hour to eliminate this tedious and time-consuming process.

c. Division of System Into Zones

The division of the system into zones is shown in Figure 8. The over-all dimensions of the system are the same as those of Figure 1. Because steady state conditions are considered, the core must be terminated at a given distance from the front of the drill and either the temperature or heat flux at the termination must be specified. A core whose length increases with time was not included because of our assumption of steady state conditions. We terminated the core at a distance of 27.8 inches from the front of the drill and assumed that this boundary is at constant temperature of $470^{\circ}K$, i.e., by the time the core is 27.8 inches or longer, the part of the core that is out of the system is in equilibrium with the radiating environment.

The zones near the drill front, where heat is generated, were chosen to be of small thickness. This is required because the diffusion of heat in the rock is dominated by convection, which introduces very thin boundary layers. In these thin layers, the temperature decreases very sharply (exponentially) from very high values at the source to the low ambient values. Therefore, since the method of zones uses a parabolic temperature distribution, the size of the zones must be smaller than the boundary layer if a parabola is to approximate an exponential to the required degree.

The thickness of the boundary layers is given by $2k/\rho cU$, where k, ρ and c are the thermal conductivity, density and specific heat of the rock, respectively. We have used the following values for our computer calculations:

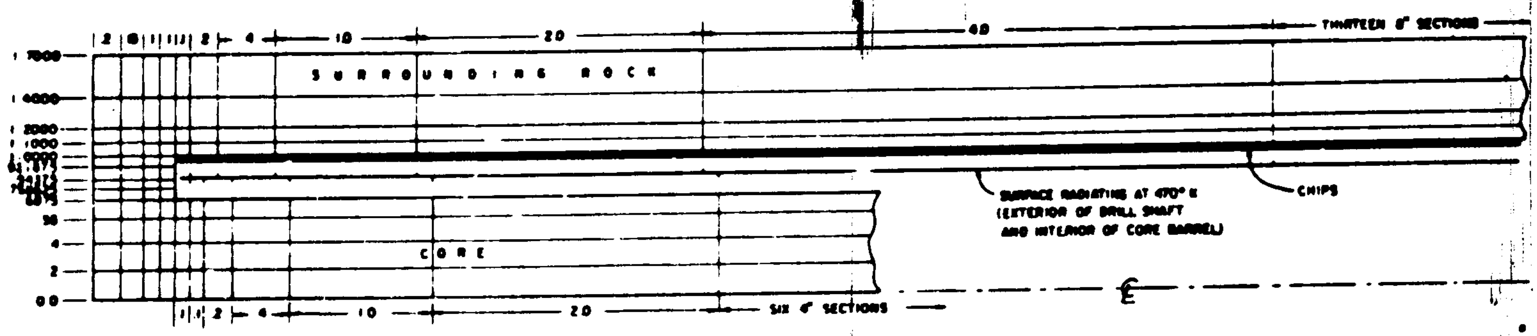


FIGURE 8 DIVISION OF SYSTEM INTO ZONES

Drilling rate (U) = 0.0508 cm/sec (or 1.2 in/min)

Conductivity of rock (k) = 0.025 watts/cm^{o}C

Product of density and specific heat of rock (ρc) = 2.8 joules/cm^3 ^{o}C

With these values, the thickness of the boundary layers is about 0.14 inches, and the dimensions of the zones near the front of the drill are smaller than this as shown in Figure 8.

The above properties approximate those of basalt. We have assumed that 3 kw of heat will be generated in drilling through this rock at the above rate. Furthermore, we have assumed that there is no cooling of the front of the drill or that the heat drawn by cooling is negligible as compared to 3 kw, so that W_2 = 3 kw. This value of W_2 may be too high for this drilling rate; however, it will establish an upper limit for the system temperatures.

As shown in Figure 8, each zone must have an interface with only one neighboring zone. This is a requirement of our computer program. We have subdivided the system into 172 rock zones. Each zone is characterized by an average volume temperature and four average surface temperatures except those zones that are on the axis of the drill. The latter are characterized by their average surface temperatures. There are 19 chip zones. Each zone is characterized by an average volume temperature and two average end temperatures in the axial direction (no radial temperature gradients in the chips are considered). We have chosen 19 zones pertaining to the external surface of the drill shaft and 12 zones pertaining to the internal surface of the core barrel. Each of these zones is characterized by a single temperature, which is constant and equal to 470^{o}K, these surfaces are assumed to radiate as black bodies at 470^{o}K.

The total number of average volume and surface temperatures for the zones is equal to 617. The number of temperatures that are fixed by the various boundary conditions is equal to 74. Thus, there are 543 unknown temperatures, and the same number of equations which have to be solved simultaneously.

d. Results Obtained From Computer Calculations

Figure 9 shows the results of the computer run. For clarity, the zones are not shown to scale. The numbers are the values of the average volume and surface temperatures of each zone (in ^{o}K).

The temperatures everywhere are consistent, except at the end of the core where no temperatures have been indicated. The computer solves the simultaneous equations by successive iterations. After several hundred iterations, the values indicated in Figure 9 and some values for the end part of the core were obtained. From then on, for several hundred additional iterations, the only values that changed were those at the end of the core. The computer found the correct solution for all temperatures except the end part of the core where the boundary condition of fixing the temperature of the end of the core at 470^{o}K is apparently inappropriate. Because the temperatures at the end of the core are both low and of limited significance, the solution obtained was satisfactory.

Several temperatures in the lower left part of the surrounding rock (in Figure 9) are approximately one degree below the ambient temperature of 230^{o}K. This is a result of round-off errors in the calculation of the conductances. Also, some temperatures in the last zones of the right part of the surrounding rock (in Figure 9) differ from those expected by one or two degrees. This also may be caused by round-off errors or the assumed condition at the right bounding surface of the surrounding rock

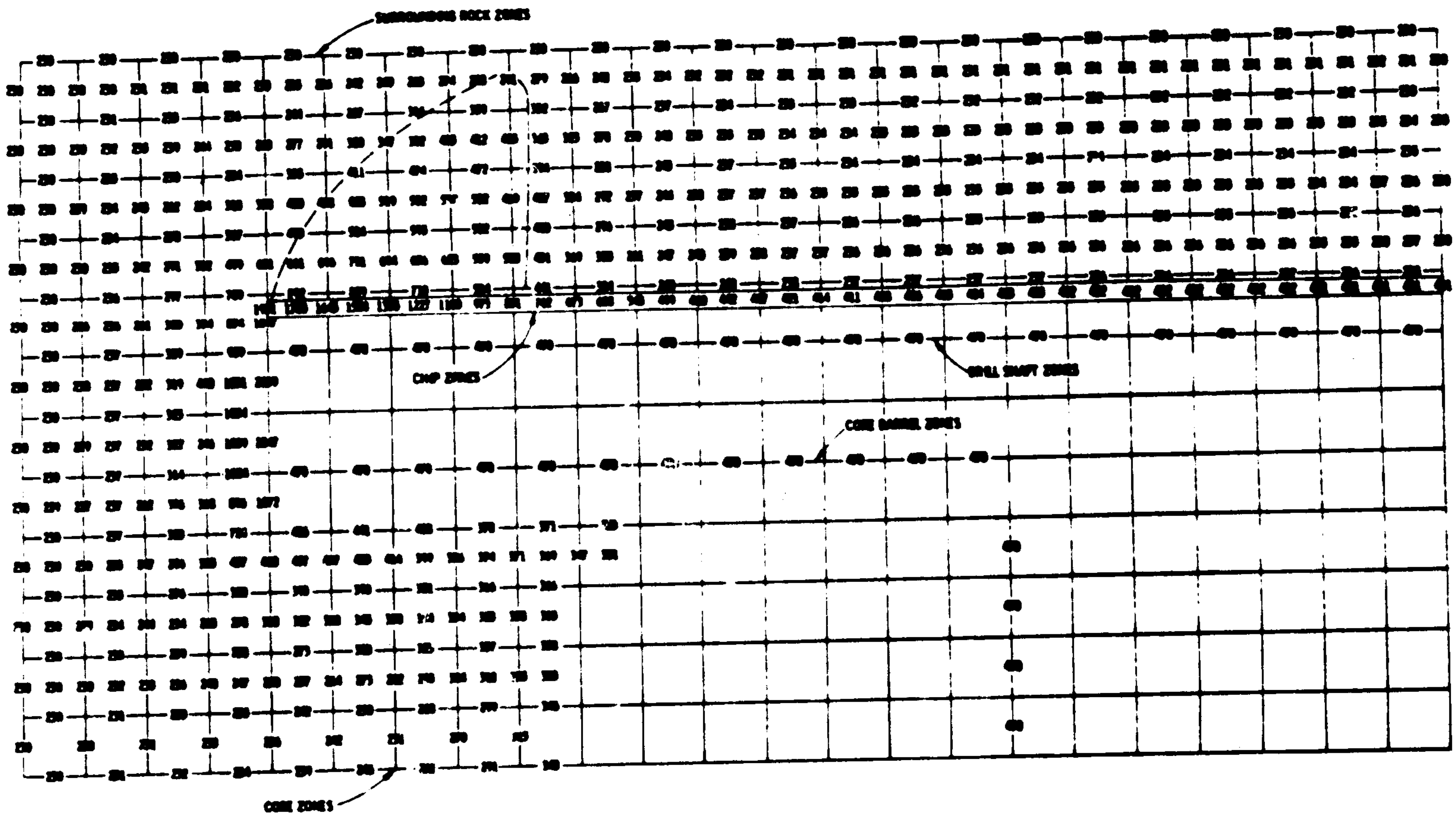


FIGURE 9 AVERAGE VOLUME AND SURFACE TEMPERATURE IN °K

(constant temperature at 230°K). The temperatures of the surrounding rock approach the ambient temperature with relatively small gradients, thereby indicating that the size of the enclosure of the system is adequate. The temperatures at the front of the drill are about 2000°K. Within a distance from the front of the drill of the order of the boundary layer thickness in both the axial and radial directions, the temperatures decrease to near ambient.

The core, as it enters the core barrel is hot at its outer edge and is near ambient temperature near its axis. At subsequent distances from the drill face, the edge of the core cools off by radiation and by diffusion of heat towards the axis of the core. The extent of core degradation caused by excessive heating can be evaluated from the temperature distribution in the core at the front of the drill, because this is the zone of maximum temperature.

In the region enclosed by the dashed lines shown in Figure 9, the surrounding rock is heated extensively by radiation from the hot chips. The heat is conducted out radially and convected to the right. The temperature distribution in the rock is like a ridge slanted to the right and with peak values near the chips.

The average surface temperatures at the plane of the front of the drill are plotted in Figure 10 as a function of radial distance from the axis. Because the temperatures are very high only on the drill face, very little heat flows into the rock; most of the heat is carried away by the chips. The temperature of the chips, as they enter the annulus to be transferred up the auger flutes, is 1951°K (see Figure 9). This corresponds to a temperature rise above the ambient temperature of 1721°C. The heat content of the chips leaving the drill face is equal to cUA times this temperature rise, where A is the area of the front of the drill.

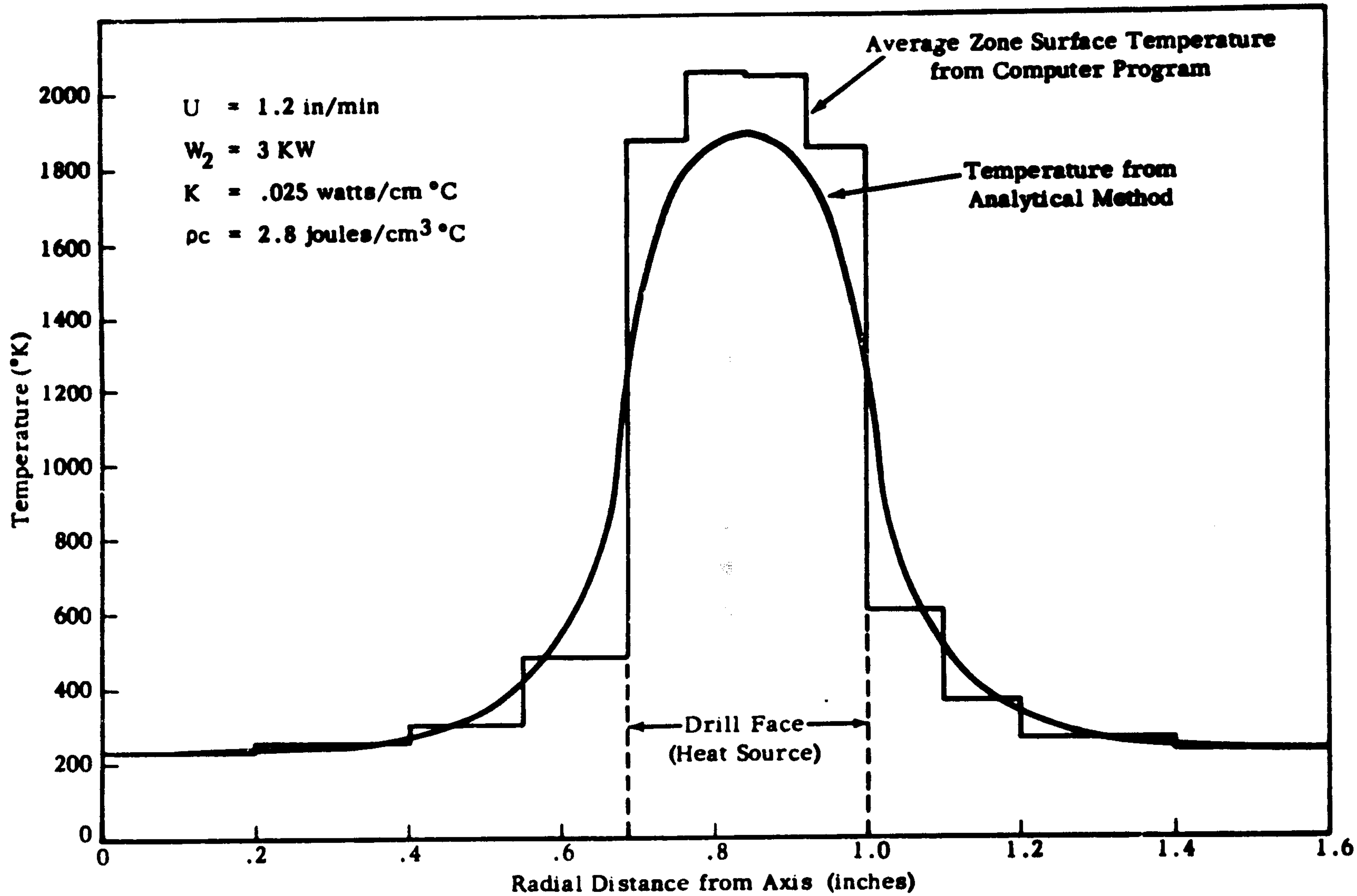


FIGURE 10 VARIATION OF THE TEMPERATURE OF THE DRILL FACE PLANE WITH RADIAL DISTANCE FROM THE AXIS

For the assumed conditions, the heat carried away is equal to 2,620 watts; i.e., 87% of the power input going to the rock and chips is carried away from the drill face by the chips.

The average core temperature rise is relatively small. For example, if the rock core were degraded when its temperature reaches 200°C, Figure 10 shows that only about 0.1 inch of the outer part of the core would be affected.

The temperature of the chips at various distances from the drill face is shown in Figure 11. The chips cool off rapidly for the conditions of "slug flow" in the annulus. Their temperature approaches the drill shaft temperature of 470°K by the time they have traveled about 8 inches up the drill shaft. Most of the heat contained in the chips is radiated to the drill shaft and the surrounding rock within the first 2 or 3 inches of the drill shaft. This is a consequence of the assumption of the full annulus mode of motion for the chips used in this example, which gives conservative results. If, instead, the spiral mode of motion had been used, the chips would cool off much more gradually.

In summary, the following results have been obtained from the computer analysis:

(1) The temperature of the rock and chips at the drill face is about 2000°K.

(2) The temperature of the surrounding rock decreases very rapidly to ambient temperature values within a distance from the drill face equal to the boundary layer thickness (0.14 in.) in both the axial and radial directions.

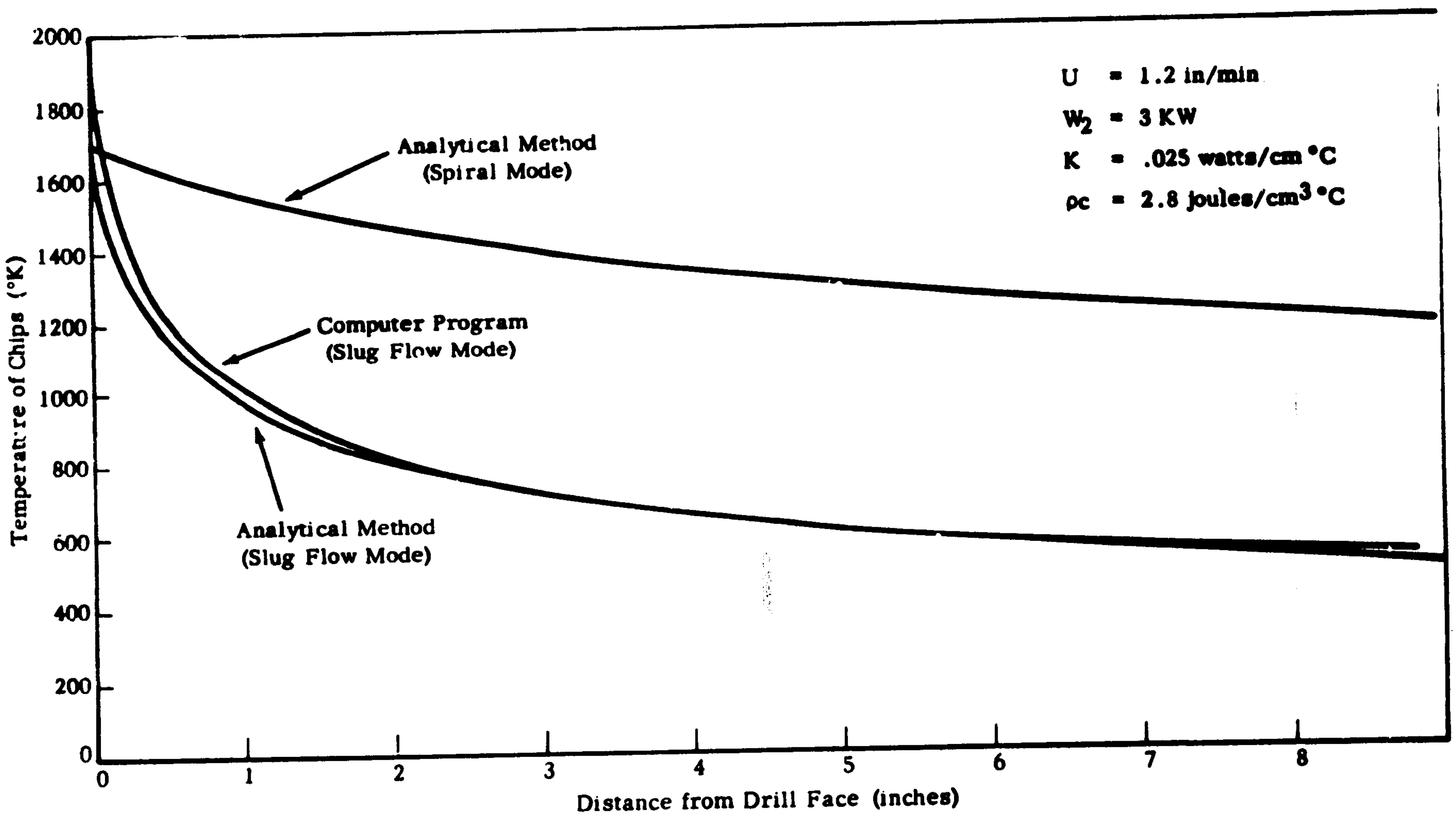


FIGURE 11 CHIP TEMPERATURE EVALUATED BY ANALYTICAL AND COMPUTER CALCULATIONS

(3) About 0.1 in. of the outer part of the core reaches temperatures higher than 200°C.

(4) About 87% of the 3 kw that is assumed to flow into the rock and chips, or 2620 watts, is carried away from the drill face by the chips.

(5) The chips cool off very rapidly for a chip motion in which the annulus is completely filled. Most of the heat contained in the chips is radiated to the surrounding rock and to the drill shaft within the first 2 or 3 inches of their travel towards the basket.

3. Analytical Approach

a. Introduction

In this section we will examine the three problems stated in the introduction to Section V individually.

Figure 12 shows the circular strip heat source which exists at the face of the drill. The chips and the surrounding moving rock are heated by this source. In the actual drill system the drill is behind the heat source; in the analytical model, the heat source is in an infinite moving medium. We have assumed that the drill does not affect the temperature of the rock near the source, particularly the rock in front of the source. We have calculated the temperature distribution on the plane of the source without the drill behind it. From this calculation, the initial temperature of the chips and the temperature in the core can be obtained.

This simplified calculation is valid because only the chips and the rock near the face of the drill are in the heat source zone and at a high temperature. Furthermore, as is shown in Appendix A, for values of the

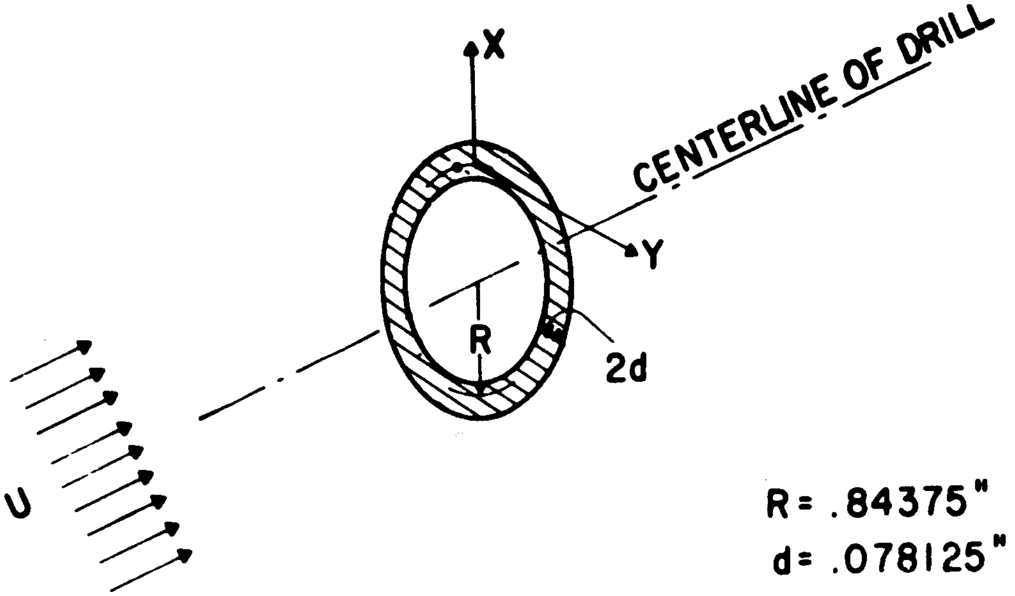


FIGURE 12 CIRCULAR STRIP SOURCE

dimensionless parameter

$$\xi = \frac{\rho c d U}{k}$$

which are equal to 1 or larger, the effect of the heat source is confined to its vicinity so that a long drill behind the source will not deplete the source significantly. For most drilling conditions, ξ is larger than 1.

Once the initial temperature of the chips has been determined, the cooling of the chips as they travel to the chip basket can be determined provided the temperature of the surrounding rock is known. The latter is, of course, not known unless all three problems are treated together, as has been done with the computer program. However, the results from the computer run described in the preceding section show that the temperature of the rock surrounding the drill shaft differs appreciably from that of the drill shaft only for a very small distance from the drill face. Therefore, in calculating the cooling of the chips in this section, we have assumed that the surrounding rock is at drill shaft temperature.

These simplifications permit calculations to be carried out in parametric form. In the following sections we will show, by comparison with the results of the computer analysis, that the accuracy of the analytical approach and the assumptions included are acceptable.

b. Initial Temperature of the Chips and Core Degradation

We have estimated the initial temperature of the chips and the temperatures of the core from the temperature distribution on the face of a circular strip source in a moving medium (Figure 12). This temperature distribution can be formulated in terms of a double integral whose evaluation is difficult. However, as shown in Appendix A, when the radius of curvature of the source (R) is large as compared to the half-width of the source (d), the temperature distribution at the face of the circular source may be approximated by that of a strip heat source. Folding the straight source around to form a circular source will not have a significant effect on the temperature distribution near the source provided R/d is large and β is 1 or larger.

The results of these calculations are shown in Figure 13. The average temperature rise of the face of the source, which is also assumed to be the initial temperature of the chips, is shown in Figure 14. These figures confirm the assumption that, for large values of β, the effect of the heat source is confined to its vicinity. Figure 13 shows that the temperature approaches ambient values at a distance of 2d from the center of the source. These results also confirm the appropriateness of folding around a strip heat source to form a circular source.

From Figure 14, the quantity of heat carried away by the chips can be determined. The value of the ordinate is equal to the ratio of the heat carried away by the chips to the total heat flowing into the rock and chips (W_2). Thus, for the values of β equal to 3 or larger, 80% or more of W_2 is carried away by the chips.

Examples

For the drill shown in Figure 1, we have:

$$d = .078125 \text{ in.} = .39685 \text{ cm}$$

$$A = 10.69 \text{ cm}^2$$

We have chosen the following values for rock properties:

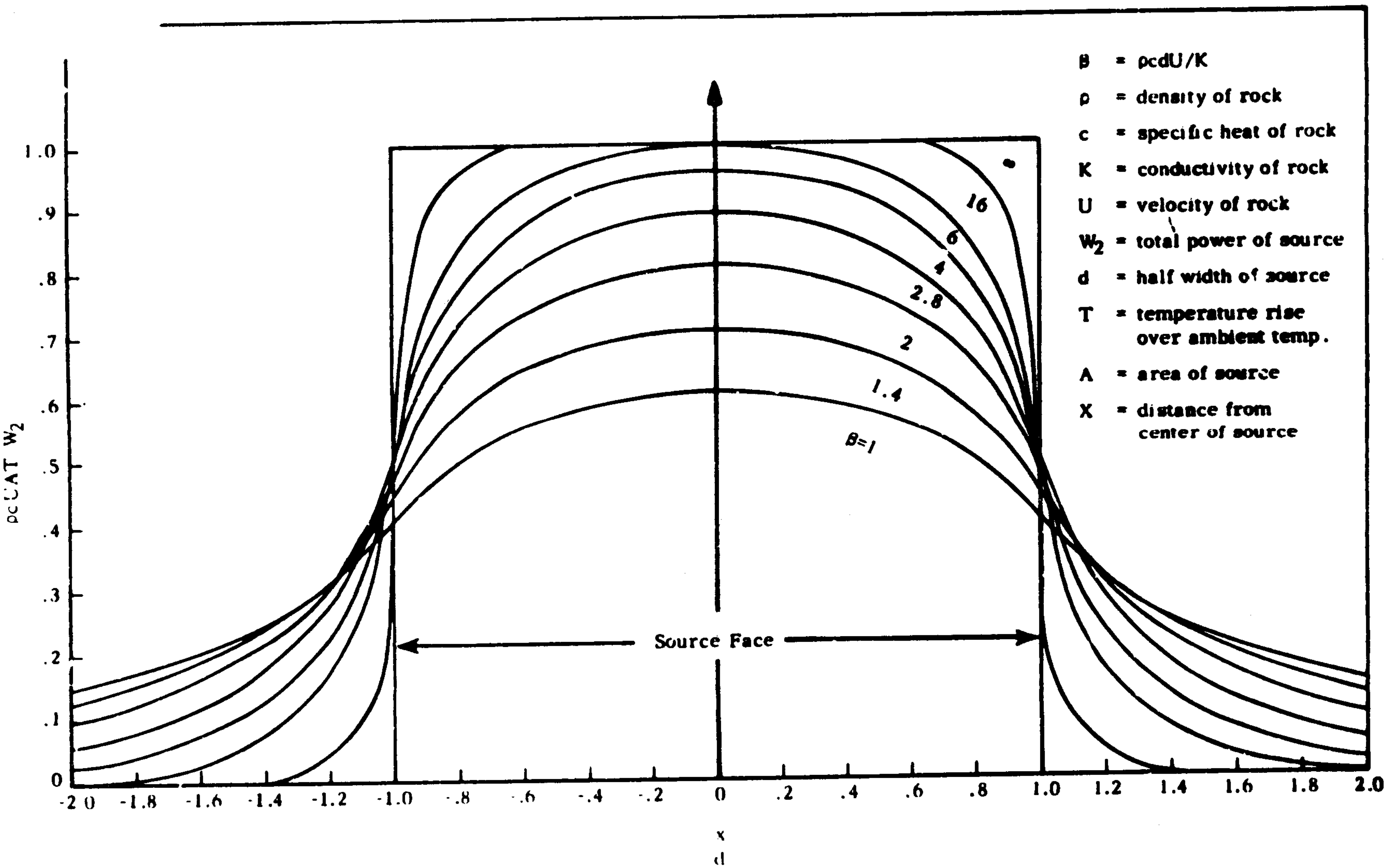


FIGURE 13 TEMPERATURE DISTRIBUTION ON THE PLANE OF A CIRCULAR STRIP SOURCE

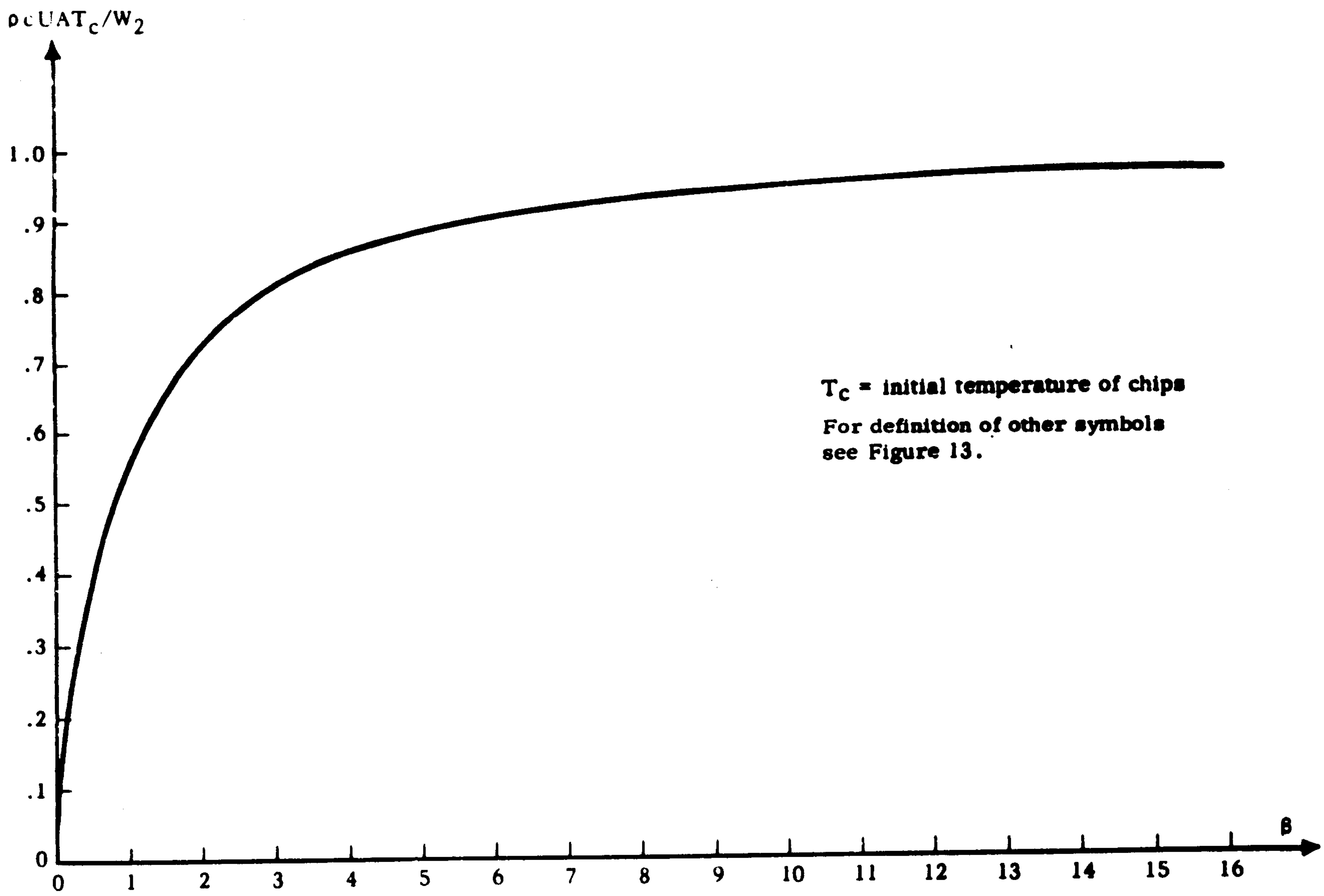


FIGURE 14 AVERAGE TEMPERATURE RISE OF THE HEAT SOURCE OR INITIAL TEMPERATURE RISE OF THE CHIPS

$$\rho c = 2.8 \text{ joules/cm}^3 \text{ }^\circ\text{C}$$

$$k = 0.025 \text{ watts/cm }^\circ\text{C}$$

If the drilling rate is 1.2 in/min., and all 3 kw supplied to the drill face spreads in the rock or is carried away by the chips,

then

$$U = 0.0508 \text{ cm/sec}$$

$$W_2 = 3000 \text{ watts}$$

The value of the parameter β is equal to:

$$\beta = \frac{\rho c d U}{k} = 2.26$$

and:

$$\frac{W_2}{\rho c U A} = 1974$$

Then from Figure 13, the temperature rise distribution on the plane of the source can be obtained. Adding the ambient temperature of 230°K, the result has been shown in Figure 10. These analytical results compare well with those obtained from the computer calculations. For example, this method gives a value of about 1890°K for the peak temperature, approximately 8% lower than that obtained by the computer analysis.

From Figure 14:

$$\frac{\rho c U A T_c}{W_2} = .75$$

This indicates that 75% of the 3 kw is carried away by the chips as compared to 87% found by the computer analysis. The initial temperature of the chips, T_c, is equal to 1710°K (adding the 230°K ambient temperature) as compared to 1950°K. These discrepancies are due mainly to the boundary condition that, in the computer analysis, the chips give off heat near the front of the drill by radiation. Thus, the temperatures at the front of the drill should be higher in the computer run.

If the drilling rate is 2.4 in/min., and the other parameters remain the same, then:

$$\beta = 4.52$$

$$\frac{W_2}{\rho c U A} = 987$$

As Figure 14 shows, more heat is now carried away by the chips (87%) but the initial temperature of the chips is only 1090°K.

On the other hand, if we take W_2 = 1500 watts, then the initial temperatures of the chips are equal to 970 and 660°K for drilling rates of 1.2 and 2.4 in/min., respectively.

The effect of rock properties is described below. As the thermal conductivity of the rock is decreased, more heat is carried away by the chips and their initial temperature increases. However, for conductivities smaller than the one we used above, the effect is small since the ordinate of Figure 14 has almost approached an asymptotic value. The effect of ρc is much greater. As ρc increases, the amount of heat carried away by the chips increases slowly (because the asymptotic value shown in Figure 14 is approached); but the initial temperature of the chips decreases almost in direct proportion to ρc. However, for most solid rocks the variation of k is much larger than the variation of ρc.

Figure 10 shows that only about 0.06 in. of core edge will be at a temperature higher than 200°C. As ρc and U increase, and as k and W_2 decrease, the potential thermal degradation of the core diminishes.

c. Cooling of Chips

We have examined the mechanism of heat exchange between the chips and the surrounding rock. Based upon this examination, we have concluded that heat transfer between the chips and the shaft is primarily by thermal radiation. We assumed that the surrounding rock is at drill shaft temperature.

The differential equation of cooling of the chips is:

$$cM \frac{dT}{dz} + 2\sigma S \; (T^4 - T_s^4) = 0$$

where:

c = specific heat of chips (equal to that of rock)

M = mass flow of chips

z = distance from drill face

σ = Stefan - Boltzman constant (5.67×10^{-12} watts/cm^2 $^oK^4$)

T = chip absolute temperature

T_s = drill shaft absolute temperature

S = view factor per unit length of z.

Subject to the boundary condition that at $z = 0$, T must be equal to the initial temperature of the chips (T_c), the solution of this equation is

$$\frac{4\sigma S T_s^3 z}{cM} = \tan^{-1} \frac{T}{T_s} - \tan^{-1} \frac{T_c}{T_s} + \tanh^{-1} \frac{T_s}{T} - \tanh^{-1} \frac{T_s}{T_c}$$

This equation is plotted in Figure 15 for three values of the parameter T_c/T_s.

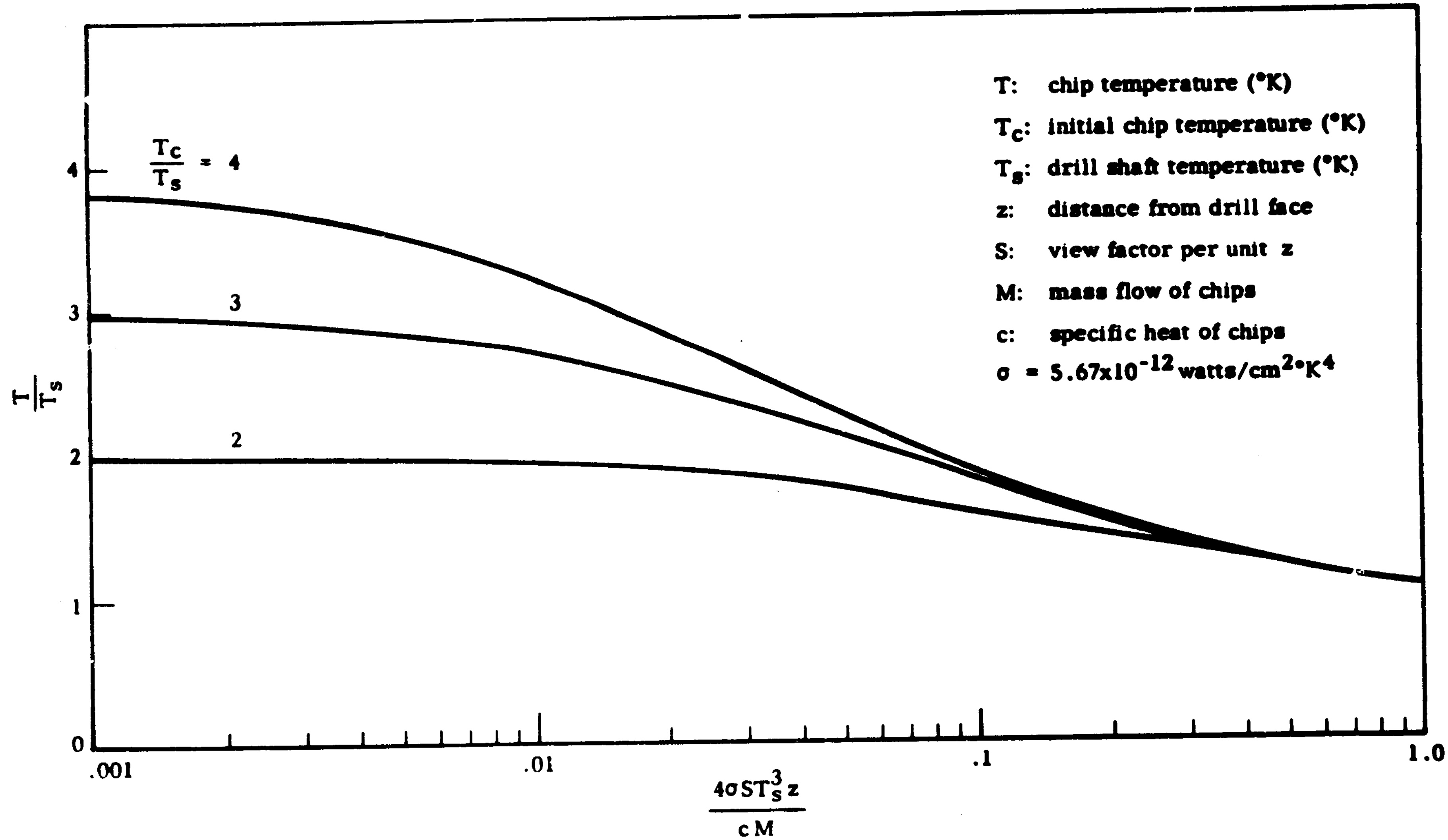


FIGURE 15 PARAMETRIC ANALYSES OF CHIP TEMPERATURE DISTRIBUTION

Examples

For the slug flow mode of motion we have:

$$cM = \rho cAU$$

from conservation of mass considerations, and:

$$S = \pi D$$

where D is the diameter of the drill. Using:

$$\rho c = 2.8 \text{ joules/cm}^3 \, {}^oC$$

$$A = 10.69 \text{ cm}^2$$

$$U = .0508 \text{ cm/sec}$$

$$D = 2 \text{ in} = 5.08 \text{ cm}^2$$

we obtain:

$$cM = 1.52 \text{ watts/}{}^oC$$

$$S = 15.96 \text{ cm}$$

Thus, for $T_s = 470^oK$:

$$\frac{cM}{4\sigma S T_s^{\,3}} = 40.5 \text{ cm} = 15.9 \text{ in}$$

and, for $T_c = 1710$, which corresponds to $W_2 = 3{,}000$ watts and k = .025 watts/cm^{o}C, we have:

$$\frac{T_c}{T_s} = 3.64$$

From Figure 15, the variations in temperature of the chips as a function of the distance from the drill face have been obtained. These values are shown on Figure 11. Except for the initial values of the chip temperature, the agreement with the results of the computer analysis is excellent.

The chips radiate most of their heat to the surrounding rock and to the drill shaft within the first 2 or 3 inches. The chips are carrying about 2250 watts from the face of the drill and radiate about 1000 watts to the drill shaft within this distance.

For the spiral mode of motion cM is one-half the above value, since the pitch of the auger is 30°. To calculate S we must know the cross dimensions of the layer of the chips moving up the auger. Assume that the chip layer is a rectangle with a width w equal to that of the auger and a height h. Then

$$S = w + h$$

If

$$w = .04 \text{ in.}, \ h = .125 \text{ in.}$$

then

$$S = .419 \text{ cm}$$

All the other parameters have the same values as above. The only difference here is that:

$$\frac{cM}{4 \sigma S T_s^3} = 303 \text{ in.}$$

The decay of the chip temperature with distance from the drill face can now be computed from Figure 15. The results are compared in Figure 11. In this mode, the chips cool much more gradually than with the slug flow mode of motion. The chip temperature all the way up to the chip basket, which is about 8 ft. from the drill face, is shown in Figure 16. When the chips arrive at the basket, they are still at a temperature of about 610°K.

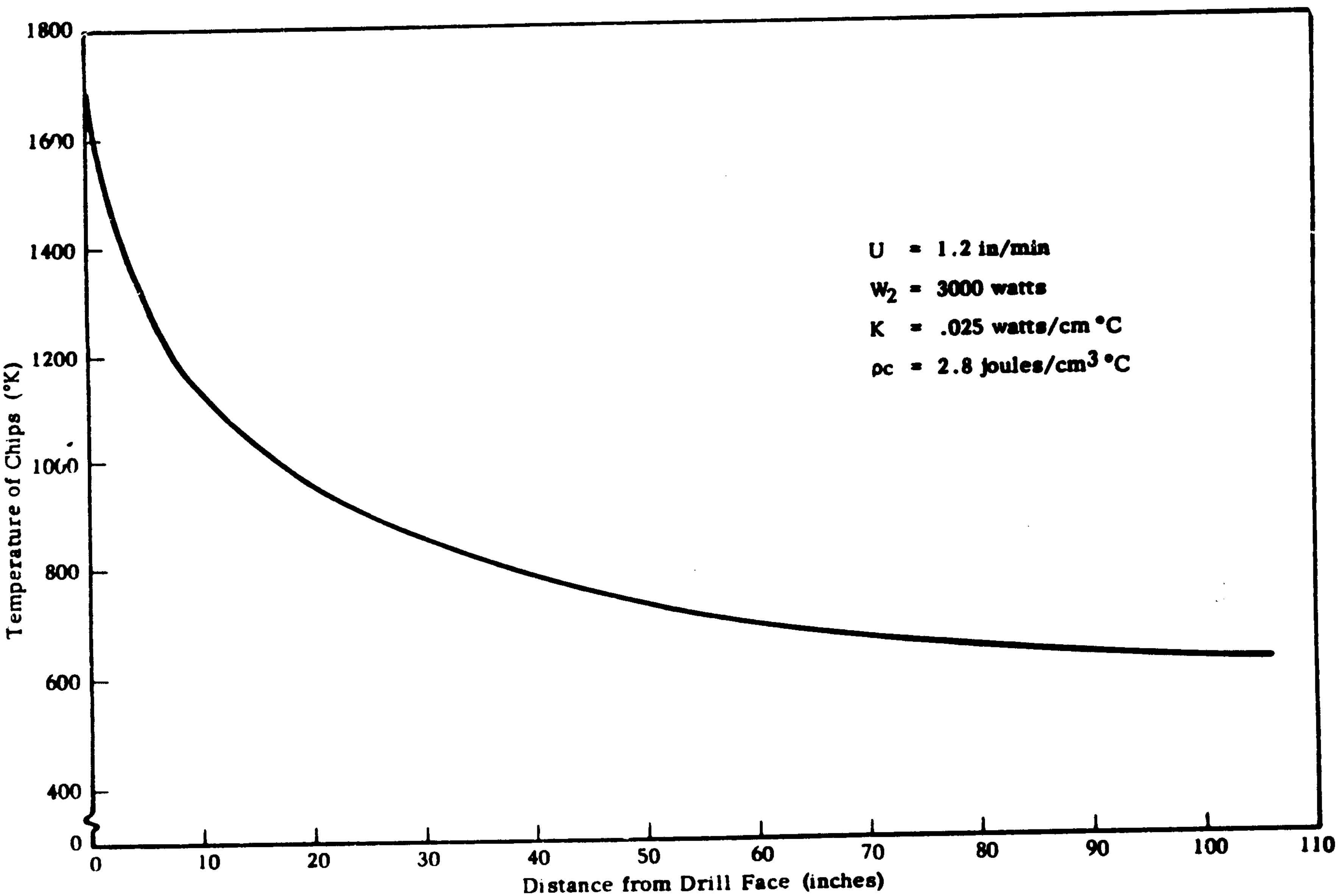


FIGURE 16 CHIP TEMPERATURE EVALUATED FOR SPIRAL MODE OF MOTION

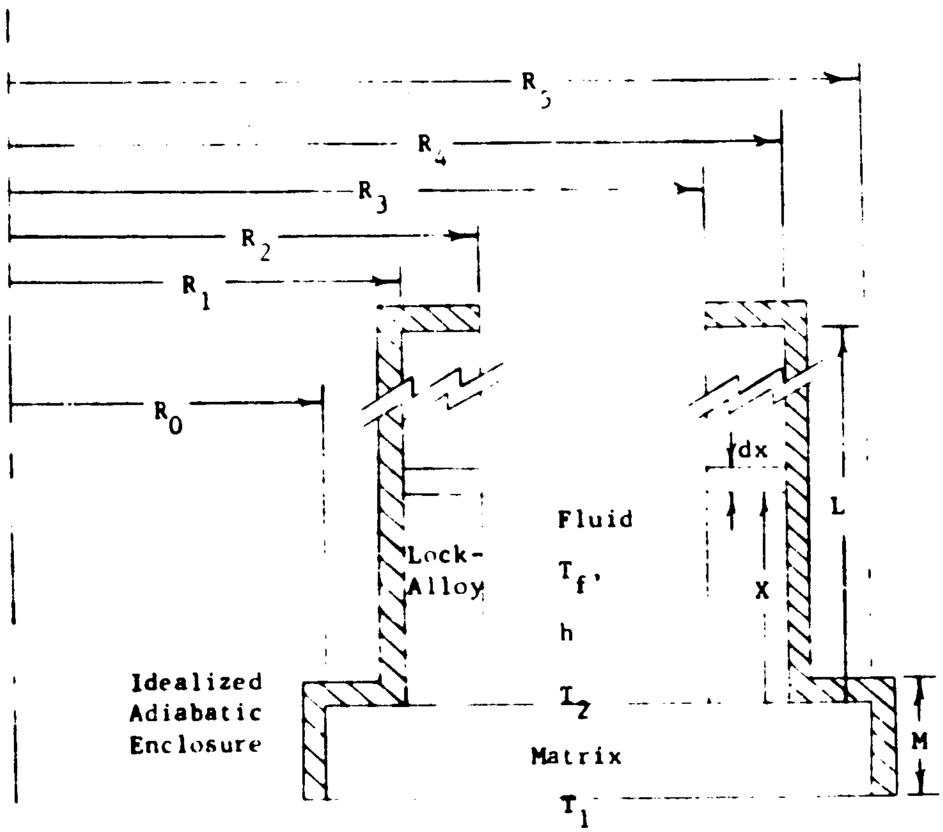
B. MATRIX, DIAMOND, AND COOLING SYSTEM CALCULATIONS

1. Heat Transfer in the Matrix and Cooling System

In order to establish the relationships between the heat flow in the matrix and the temperature distribution near the cooling zone of the drill, an approximate analysis was conducted using the analytical model and techniques described below. The objective of the analysis was to determine the drill face temperature and temperature distribution in the drill (near the bit) as a function of the power removed by the cooling water in the drill. The effects of the cooling water-drill heat transfer coefficient on drill temperatures were investigated.

a. Assumptions Used in Model

The model used for the analysis is shown in the following diagram:



The assumptions used in analysis were:

(1) Heat flows only vertically upward through the matrix until the cooling fluid is reached. Heat is distributed uniformly over the bottom of the matrix area.

(2) Heat flows vertically upward through the Lockalloy drill shaft tubes.

(3) Heat is transferred to the fluid (with an average heat transfer coefficient h) from

(a) the bottom annulus (considered to be the top of the matrix), and

(b) the Lockalloy tube walls.

(4) The exterior radial surfaces of the matrix and drill are adiabatic (no flux) surfaces.

(5) The cooling fluid temperature is constant.

With these assumptions, radial temperature gradients in the matrix and tube walls may be neglected. The effects of non-uniform heat distribution over the matrix are discussed in Section V-B-2. The only assumption which needs additional justification is (4). In the actual drill system, the inner tube wall surface exchanges heat with the core barrel by radiation. Because the core barrel temperature is not very high (see Section IV-A) this heat transfer will be small compared to the heat flowing axially from the drill face through the matrix. On the exterior surface of the matrix and drill, there is inward radial heat flow from the hot chips. The magnitude and distribution of this heat flow has already been discussed. By neglecting this heat source, we will have calculated the minimum temperature in the matrix surface and drill shaft walls; the actual temperatures will be higher. Thus, these calculations will provide an upper limit to the amount of heat that can be withdrawn from the matrix to the cooling water for various drill face temperatures.

b. Calculations

For the two annular disc sections of the drill wall at height x.

Let T = temperature of metal at height x

Let $A = \pi(R_4^2 - R_3^2) + \pi(R_2^2 - R_1^2)$

Let $B = 2\pi(R_3 + R_2)$; then

Heat Input to discs by conduction $= -k\ (A)\ (\frac{dT}{dx})$

Heat Output from discs by conduction $= -[kA \frac{dT}{dx} + \frac{d}{dx}\ (kA \frac{dT}{dx})\ dx]$

Heat Output to cooling water $= hB\ (T-T_f)$

At steady state, Input-Output = 0, or

$$\frac{d}{dx}\ (kA \frac{dT}{dx})\ dx - hB\ (T-T_f) = 0 \qquad \text{(B-1)}$$

We may assume that k, h, A, and B are independent of x.

Therefore,

$$kA \frac{d^2T}{dx^2} - hB\ (T-T_f) = 0 \qquad \text{(B-2)}$$

The solution to this equation for our boundary conditions (which are (1) at $x = 0$, $T = T_2$, and (2) at $x = L$, $\frac{dT}{dx} = 0$) is:

$$\frac{T-T_f}{T_2-T_f} = \frac{e^{GX} + e^{G(2L-X)}}{1 + e^{2GL}} \qquad \text{(B-3)}$$

where G is defined as the positive value of $\sqrt{\frac{hB}{kA}}$.

The total heat transferred to the fluid is equal to

$$Q_1 = \underbrace{h\ (\pi)(R_3^2 - R_2^2)(T_2 - T_f)}_{\text{from base to fluid}} + \underbrace{hB \int_0^L (T - T_f)\ dx}_{\text{from walls to fluid}} \qquad \text{(B-4)}$$

Substituting Equation B-3 in B-4 and integrating, we obtain

$$Q_1 = h\ (\pi)(R_3^2 - R_2^2)(T_2 - T_f) \left[1 + \frac{2}{(R_3 - R_2)\ G} \left(\frac{e^{2GL} - 1}{e^{2GL} + 1}\right)\right] \qquad \text{(B-5)}$$

Thus, the walls of the drill transfer heat to the fluid in relation to the base of the fluid channel, in the proportion

$$\frac{2}{(R_3 - R_2)\ G} \left(\frac{e^{2GL} - 1}{e^{2GL} + 1}\right) : 1$$

The total heat flow Q_1 is equal to the flow upward through the matrix:

$$Q_1 = k_m\ \pi(R_5^2 - R_o^2)\left(\frac{T_1 - T_2}{M}\right), \text{ or} \qquad \text{(B-6)}$$

$$T_1 - T_2 = \frac{Q_1 M}{(k_m)(\pi)(R_5^2 - R_o^2)} \qquad \text{(B-7)}$$

Thus if the heat flowing upward into matrix is specified as W_1, then

$$Q_1 = \frac{W_1 \text{ watts}}{0.293 \text{ watt-hr/Btu}} = \frac{W_1}{0.293} \frac{\text{Btu}}{\text{hr}} \qquad \text{(B-8)}$$

We can solve the above equations for T_2:

$$T_2 = T_f + \frac{W_1}{[0.293][h][\pi][R_3^2 - R_2^2]\left[1 + \frac{2}{(R_3 - R_2)\ G}\left(\frac{e^{2GL} - 1}{e^{2GL} + 1}\right)\right]} \qquad \text{(B-9)}$$

and then for

$$T_1 = T_2 + \frac{W_1 M}{[0.293][k_m][\pi][R_5^2 - R_o^2]} \qquad \text{(B-10)}$$

T at any value of x has already been derived; once T_2 is known, T can be determined from:

$$T = T_f + \left[T_2 - T_f\right]\left[\frac{e^{GX} + e^{G(2L-X)}}{1 + e^{2GL}}\right] = T_f + \left[T_2 - T_f\right]\left[\frac{\cosh\ (G(L-X))}{\cosh\ (GL)}\right] \qquad \text{(B-11)}$$

(In all three of these relationships, G is defined as the positive square root of $\frac{hB}{kA}$.)

Working in the English system of units, and converting our conductivities,

k (for Lockalloy) = 2.05 watt/cm-°C = 118.4 Btu/hr-ft-°F

k_m (for matrix) = 0.5 watt/cm-°C = 28.9 Btu/hr-ft-°F

For our case (40-mil Lockalloy walls):

R_o = 0.704 in = 0.0587 ft

R_1 = 0.794 in = 0.0662 ft

R_2 = 0.834 in = 0.0695 ft

R_3 = 0.910 in = 0.0758 ft

R_4 = 0.950 in = 0.0792 ft

R_5 = 0.990 in = 0.0825 ft

L = 1 to 5 feet

M = 0.167 in = 0.0139 ft

h = 10 to 1000 Btu/hr-ft^2-°F

T_f = 390°F

$$A = (3.142)(0.0792^2 - 0.0758^2 + 0.0695^2 - 0.0662^2) = 0.00306 \text{ ft}^2$$

$$B = (2)(3.142)(0.0758 + 0.0695) = 0.913 \text{ ft}$$

$$G = \sqrt{\frac{hB}{kA}} = \sqrt{\frac{(0.913)(h)}{(118.4)(0.00306)}} = 1.59\sqrt{h}$$

c. **Results and Discussion**

Solution of Equations B-9, 10 and 11 using the above values leads to the results shown in Figures 17, 18, and 19. In Figure 17, we have plotted the temperature profile in the drill rod and matrix as a function of heat flowing into the drill (W_1). The calculations were carried out for a heat transfer coefficient of 20 Btu/hr ft^2 $^{\circ}$F. This value is the lowest expected for boiling heat transfer (even under film-boiling conditions) and is also a reasonable value for convective heat flow by a water stream. Note that for up to 700 watts flowing through the matrix, the temperature drop is only about 100°F across the matrix.

Figure 18 shows the effect of heat transfer coefficient h on the temperature rise of the diamond-matrix surface for various heat inputs to the drill. In Figure 19 we have shown the fraction of the total heat input which is transferred to the cooling water by the walls of the drill passages.

Equation B-9 gives some interesting information regarding the effect of Lockalloy drill shaft length on heat transfer. The term:

$$\frac{e^{2GL} - 1}{e^{2GL} + 1} \quad (\text{or } \tanh [GL])$$

tends toward an "asymptotic" value of 1.0 as GL increases. However, it reaches a value of 0.999 at a value of GL = 3.6. If we assume even a

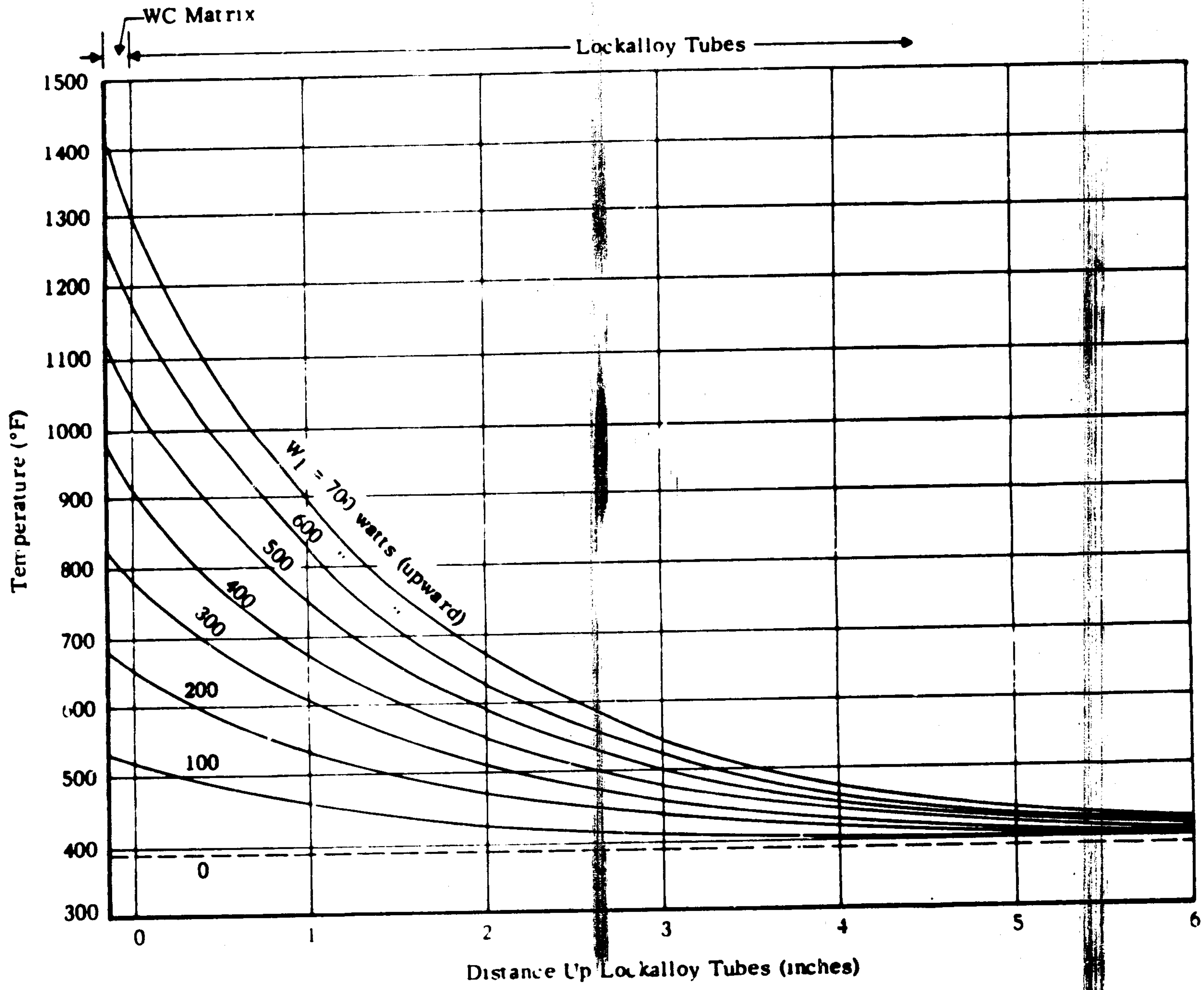


FIGURE 17 TEMPERATURE PROFILE IN MATRIX AND DRILL

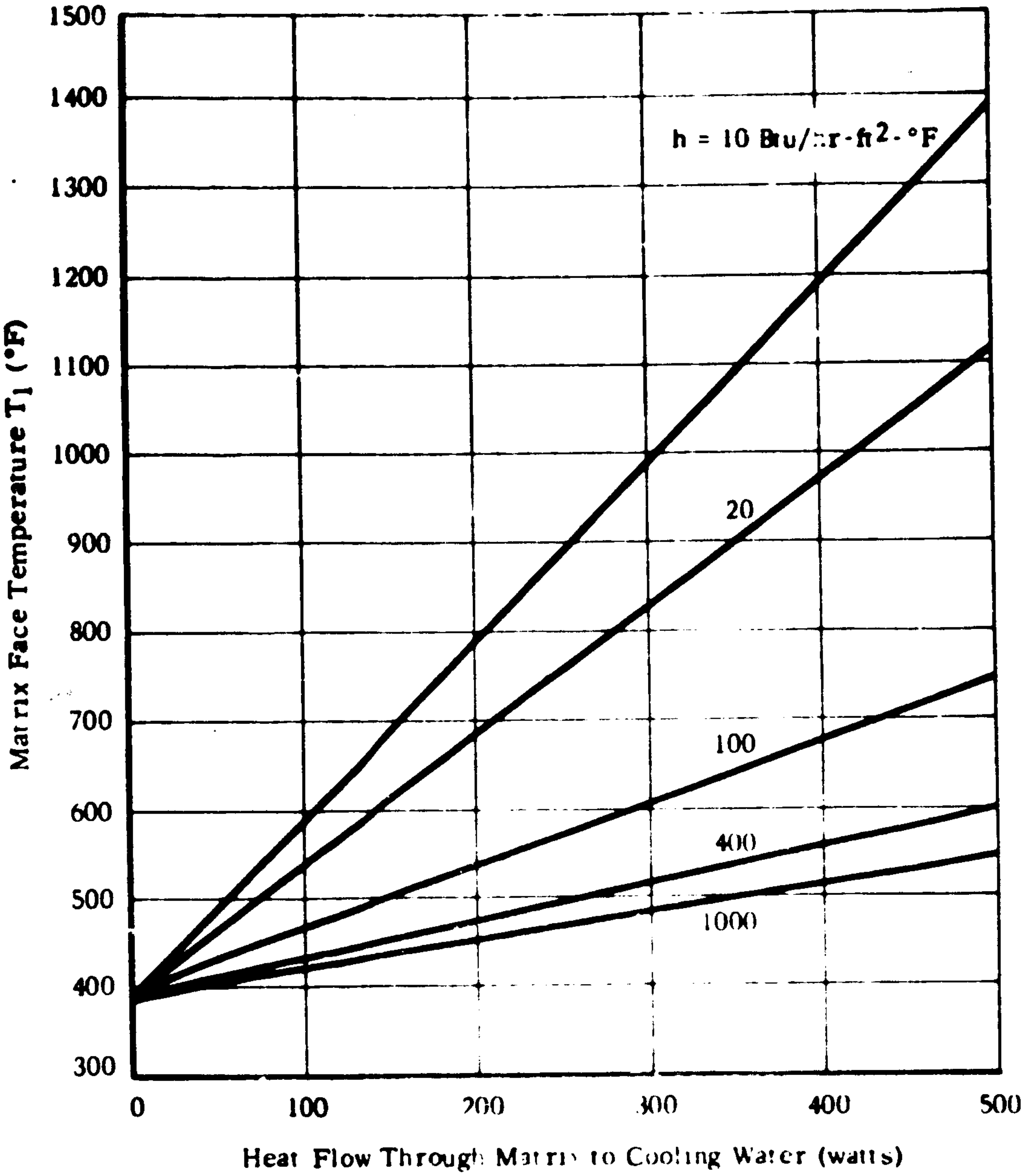


FIGURE 18 TEMPERATURE OF MATRIX FACE AS A FUNCTION OF HEAT FLOWING INTO COOLING WATER

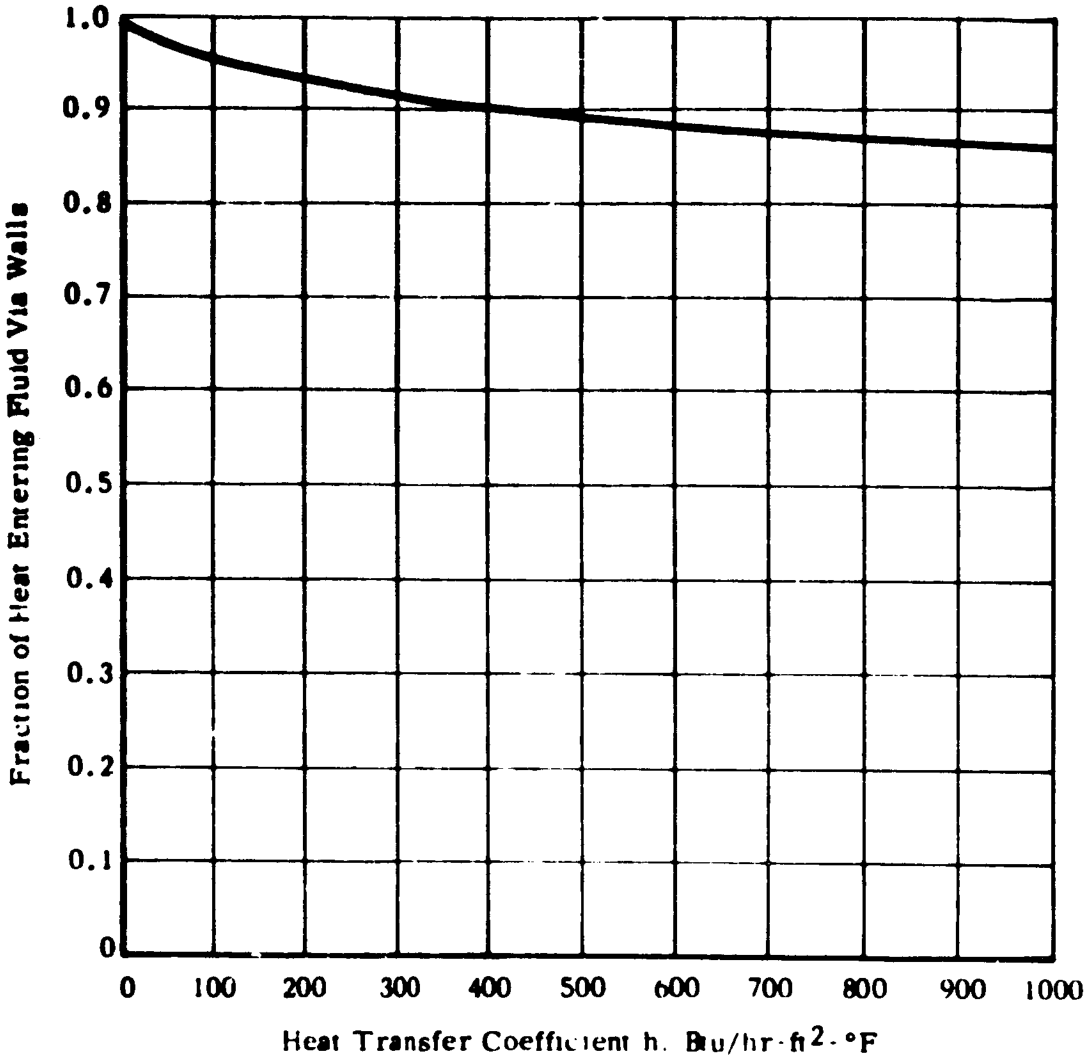


FIGURE 19 RELATIVE PROPORTION OF HEAT ENTERING COOLING WATER VIA TUBE WALLS

value as low as 10 for h, G = (1.59 ($\sqrt{10}$) = 4.86. If GL is to exceed 3.6, all that is required is that L exceed 3.6/4.86 = 0.74 ft. Thus, even for the worst value of h, a Lockalloy tube wall length of 9 inches is as effective as a Lockalloy wall of infinite height (within one part in a thousand) in transferring the heat to the cooling water. At larger values of h, even shorter walls become as effective as infinitely long walls. This indicates that all the heat flowing through the matrix is transferred to the cooling water in a very short length along the drill wall.

$$T = T_f + [T_2 - T_f] [\cosh(GX) - \sinh(GX) \tanh(GL)] \quad \text{(B-12)}$$

As noted above, tanh(GL) will always be approximately equal to unity for the system conditions we have chosen, so that

$$T \cong T_f + [T_2 - T_f] [\cosh(GX) - \sinh(GX)] = T_f + (T_2 - T_f) e^{-GX} \quad \text{(B-13)}$$

Thus, $(T - T_f)$ decays exponentially with GX, and is independent of L as long as L exceeds a few inches, as shown above. This exponential decay in temperature along the drill wall is shown in Figure 17. The above equations also shows the effect of the cooling fluid temperature. A change in the cooling fluid temperature changes the temperatures in the system by an equal amount.

Based upon this analysis, it is seen that with a modest choice of heat transfer coefficient of 20 Btu/hr ft^2 $^\circ$F, 500 watts may be withdrawn through the matrix before the diamond-matrix interface temperature reaches 1110°F (600°C) and 750 watts may be withdrawn before a temperature of 1470°F (800°C) is reached.

For these conditions, the values given above represent the **maximum** heat that can be transferred through the matrix into the cooling water. In the actual drill system, this will be diminished because of heat input from the chips and the non-uniform heat dissipation of heat at the diamond-matrix interface.

2. Heat Transfer Between the Diamonds and the Matrix

In the above analysis, the heat flowing into the matrix was assumed to be uniformly distributed over the matrix area. This is equivalent assuming that there is no difference in the diamond and matrix temperatures. Because the actual distribution of heat initially established in the chips, solid rock, or diamonds is not known, we have assumed several limiting conditions and calculated the effects on drill temperatures.

The assumption that there is zero difference between the matrix and diamond temperatures represents a condition where all of the heat dissipated in the cutting zone is generated in the rock and chips. Then the portion flowing through the matrix is transferred by radiation and contact conduction from the rock and chips. Since the exposed diamond area is only five per cent of the total face area, the effect of the diamonds may be neglected for this mode of heat input to the face. Therefore, the diamond temperature, T_d, is equal to T_1 as discussed in Section V-B-1. The values obtained are the minimum diamond temperature for a given fixed value of heat transferred into the matrix and cooling system, or, equivalently, the maximum heat flow for a given diamond-matrix interface temperature.

The upper limit for the diamond temperature may be calculated by assuming that all of the heat W_1 flows into the matrix through the diamonds. With this assumption, the temperature difference $T_d - T_2$ is greater than the difference $T_1 - T_2$ for a uniform heat source on the matrix face because the diamonds are a localized heat source and must have locally higher temperature gradients.

We have used the following assumptions regarding the diamonds and their mounting in the matrix:

1. The 78 face-set diamonds do all of the work in drilling and transfer all of the heat to the matrix. The work and heat load are shared equally by the 78 diamonds. To the extent that OD and ID gauge stones share the work and heat, mechanical loading and temperature of the face diamonds will be reduced. Therefore, this is a conservative assumption.

2. The diamonds are at a uniform temperature through their volume (effectively infinite thermal conductivity).

3. There is no heat flow resistance at the interface between the diamonds and the matrix.

One estimate of the temperature difference $T_d - T_2$ may be based on the model of a hemispherical source for heat flowing into a semi-infinite body of matrix material (MacAdams 1951). For an assumed matrix conductivity of 0.5 watt/cm^{o}C and 78 diamonds sharing the heat flow into the matrix (W_1), we obtain:

$$T_d - T_2 = \frac{W_1}{78 \times 2\pi k_m r_d} \left(1 - \frac{r_d}{r_2}\right) \qquad \text{(B-14)}$$

If we take r_2 as large compared to the radius of the diamond, then

$$T_d - T_2 = 0.192\ W_1 \qquad \text{(B-15)}$$

where $T_d - T_2$ is in ^oF and W_1 is in watts.

For the case of uniform heat dissipation over the diamond-matrix interface (discussed in 1, above), we obtain the equation $T_d - T_2 = 0.155\ W_1$. In an actual drill system, the surface at temperature T_2 must be closer to the source, and the difference would be less than given by Equation B-14.

Although the ab e equation is conservative for an array of single diamonds, the diamonds in the bit are close enough together that their heat flows interact. The average distance between diamonds in the radial rows is 0.048 inch. To obtain a better approximation using the diamonds as a source for heat flowing into the matrix, we have taken a half-cylindrical surface with radius equal to the diamond radius r_d and length L_e such that the area is equal to half the surface area of four diamonds, the maximum number in a row. Using half the surface area implies that half of the diamond protrudes from the matrix. In reality, the diamonds will be deeper in the matrix with slightly more area available for heat flow which will lower the actual temperature slightly.

To determine the temperature difference resulting from heat flow from a half-cylinder source at temperature T_d to a plane at T_2, we used an analysis approximating the heat flow from a buried electrical cable (Jakob, 1949). The analysis utilizes a fictitious sink image of the source to establish heat flow lines perpendicular to the uniform temperature plane that is the actual sink. The symmetry of the source-sink heat flow lines also shows that the result is valid for the half-cylinder that we are considering.

Based on this analysis, using the same number of face diamonds in 19 rows and other properties as above, we obtain:

$$T_d - T_2 = \frac{W_1}{19 \times 4 \pi k_m L_e} \left(\ln \left[1 + 4 \left(\frac{r_2}{r_d} \right)^2 \right] \right) \qquad \text{(B-16)}$$

or

$$T_d - T_2 = 0.307 \, W_1 . \qquad \text{(B-17)}$$

where r_2 is the matrix thickness, and L_e is the equivalent row length.

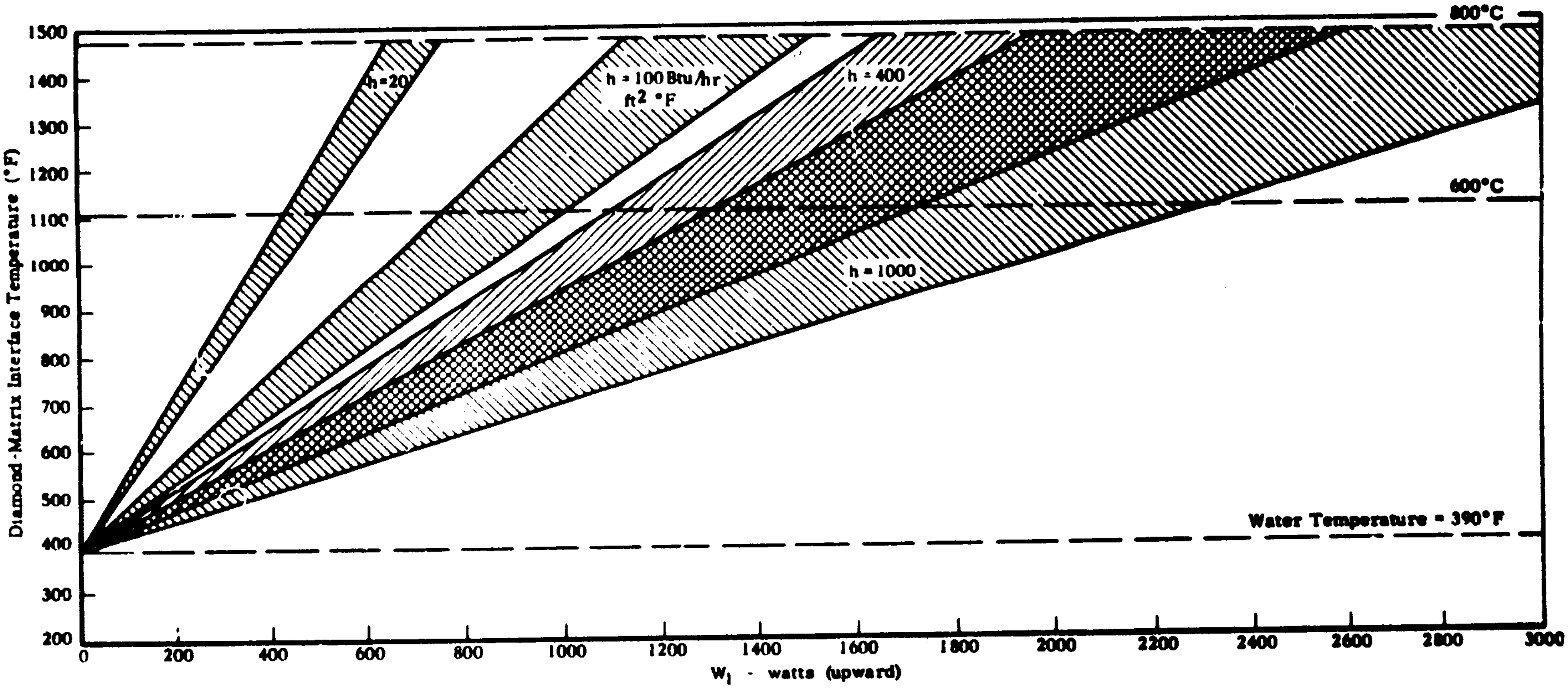
Compared to the case of a uniform heat source at the matrix face, this is an increase of 98 per cent in the temperature rise from the fluid-matrix interface to the matrix-diamond interface. Note that the diamond temperature does not increase 98 per cent. The most important contribution to the diamond temperature comes from the boiling side heat transfer, not from the matrix and diamond conductivity.

The actual temperature of the diamonds should lie between the two limiting cases of heat input uniformly to the matrix or all concentrated through the diamonds. Figure 20 shows the diamond temperatures resulting from the rise in the matrix and tube wall and that due to boiling for various heat transfer coefficients. The bands shown indicate the diamond temperature range for each coefficient value plotted.

The water-metal heat transfer area and the matrix and tube wall heat conduction areas appear to be sufficient to transfer the drill face heat inputs over a wide range of operation. Whether or not the flow annulus width (0.047 inch) in the present design is adequate to allow sufficiently rapid steam-liquid phase separation is the most important unresolved question. Water-steam phase separation in the annulus will be enhanced by the centrifugal forces that will range approximately from 40 to 160 times the local gravity force. Also, at the 220 psia operating pressure, steam volume is only 110 times the initial water volume rather than 1600 times as at 1 atmosphere pressure. Careful design of these cooling passages is essential to provide required surface heat transfer.

3. Heat Transfer Between Chips and the Diamonds

In the previous sections we have evaluated the range of temperatures for the diamond-matrix interface as a function of the heat withdrawn to the cooling water and the boiling heat transfer coefficient for several models. Before considering the over-all drill system performance, we must first examine the heat flow between the chips and the diamonds.



Note: High side of each band is calculated for diamonds as source of all heat into the matrix. Low side is calculated with a uniform heat flux over face of matrix and diamonds.

FIGURE 20 EFFECT OF HEAT FLOW INTO DIAMONDS AND MATRIX ON DIAMOND MATRIX INTERFACE TEMPERATURES FOR A RANGE OF BOILING COEFFICIENTS

The difference in the temperatures between the chips and the diamonds may be evaluated in several ways depending upon the model chosen to represent the physical system in the drilling zone.

a. Model 1, Complete Chip Mixing

If we assume that there is complete mixing and good contact between the chips and diamonds (or diamond-matrix interface), then the chips and diamond-matrix interface should be at the same temperature. Because of the rapid rotation of the drill and the force exerted on the chips by the drill, a small chip zone is expected and mixing of the chips should be good. Thus the maximum diamond temperature will be equal to the chip temperature. Any resistance to heat flow between the chips and diamonds will result in a lower operating temperature of the diamonds.

b. Model 2, "Stagnant" Chip Boundary Layer

In the absence of actual experimental data, we may assume that a "stagnant" boundary layer of chips is formed at the matrix-chip interface. The thickness of this layer is at most equal to the distance by which the diamonds protrude from the matrix. The temperature difference between the chips and the diamond-matrix interface ($T_c - T_1$) is given as:

$$T_c - T_1 = \frac{W_1 \quad \Delta X}{k_{sc} \quad A} \qquad \text{(B-18)}$$

where ΔX is the thickness of the layer, k_{sc} is the thermal conductivity of the chips in the boundary layer, A is the cutting zone area, and

W_1 is the heat flow into the matrix as before. The thermal conductivity of the hot chips in the boundary layer is difficult to evaluate; as an approximation we have assumed that the conductivity is 1/2 that of the solid rock or 0.012 watt/cm $^{\circ}$C. Using the dimensions given previously and a chip boundary layer of 0.010", we obtain:

$$T_c - T_1 = 0.39\ W_1 \qquad \text{(B-19)}$$

where $T_c - T_1$ is in $^{\circ}$F and W_1 is in watts. Thus we see that a small stagnant layer of chips provides a large resistance to heat flow. For 500 watts flowing into the matrix, a temperature difference of 195°F is encountered across a chip boundary layer of 0.010".

c. Model 3, Radiation Heat Transfer

Another extreme model is one where heat is transferred between the chips and the diamond-matrix interface only by radiation and no direct conduction heat transfer occurs. For radiative transfer only, we find that:

$$W_1 = \frac{A\,\sigma\,(T_c^{\,4} - T_1^{\,4})}{\frac{1}{\epsilon_c} + \frac{1}{\epsilon_1} - 1} \qquad \text{(B-20)}$$

where σ is the Stefan-Boltzman constant, ϵ_c and ϵ_1 are the emittances of the chip and matrix surfaces, respectively. From Equation B-20, we may derive a relationship between $(T_c - T_1)$, T_c and W_1. Even if we assume that the chip and drill face surfaces have an emittance of unity, we find that very little heat can flow by radiation from the chips to the matrix-diamond surface, unless there are larger temperature differences between the corresponding temperatures. Typical values of the heat flow (W_1) are shown in the table below for various chip temperatures and temperature differences.

Temperature Difference Between Chips and Diamond-Matrix Interface

(Radiation Cooling Model)

Chip Temperature T_c (°F)	Heat Transfered to Matrix W_1 (Watts)	$T_c - T_1$ (°F)
3000	100	120
3000	200	260
3000	500	850
3000	740	2610
----	---	----
2500	100	220
2500	200	480
2500	300	910
2500	390	2110
----	---	----
2000	100	400
2000	190	1610

Thus, we note that even at a high chip temperature of 3000°F only 740 watts could be transferred to the diamond-matrix interface (even if it were at cooling water temperature). If radiation heat exchange were the only mechanism of heat transfer between the chips and the face of the drill, the diamond temperatures would be very low and the chip temperatures high.

The radiation exchange model is a rather unlikely case, since there must be some contact between the hot chips and the drill face (or between the diamonds and the chips). Models 1 and 2 probably give a more reasonable estimate of the temperature difference between the chips and the diamond-matrix interface.

C. DRILL SYSTEM OPERATING CONDITIONS

In Section V-A, we have calculated the average chip temperatures as a function of drilling rate, rock properties and the amount of heat which flows into the rock and chips (W_2). These results were presented in dimensionless form in Figure 14. In Section V-B, we have estimated a range of diamond-matrix interface temperatures based upon the quantity of heat flowing into the matrix and cooling water (W_1). Because the sum of W_1 and W_2 must equal the total power dissipated in the system at the drill face, the diamond-matrix interface (or chip) temperatures must come to a steady-state value which satisfies the equations developed in Sections V-A and V-B. The following example will serve to illustrate these points. For a heat transfer coefficient of 20 Btu/hr-ft^2, the zone of diamond matrix interface temperatures is shown as a function of W_1 on Figure 21 (reproduced from Figure 20). For a kerf width of 0.286" (0.727 cm) used in the calculations for heat flow in the matrix, a drilling velocity of 0.102 cm/sec. (2.4 in/min) and a rock diffusivity 0.00892 cm^2/sec, we obtain a value of ξ of 4.16. From Figure 14, the value of $\rho cUT_{av}/q$ or equivalently $\rho cAUT_{av}/W_2 = 0.86$

thus:

$$T_{av} = \frac{0.86\ W_2}{\rho cUA} = \frac{0.86\ (3000-W_1)}{\rho cUA} \qquad \text{(C-1)}$$

For $c = 2.8\ \frac{\text{watt-sec}}{\text{cm}^3\ {}^\circ\text{C}}$, $U = 0.102$ cm/sec and $A = 9.8$ cm^2

we obtain:

$$T_{av} = .307\ (3000 - W_1) \qquad \text{(C-2)}$$

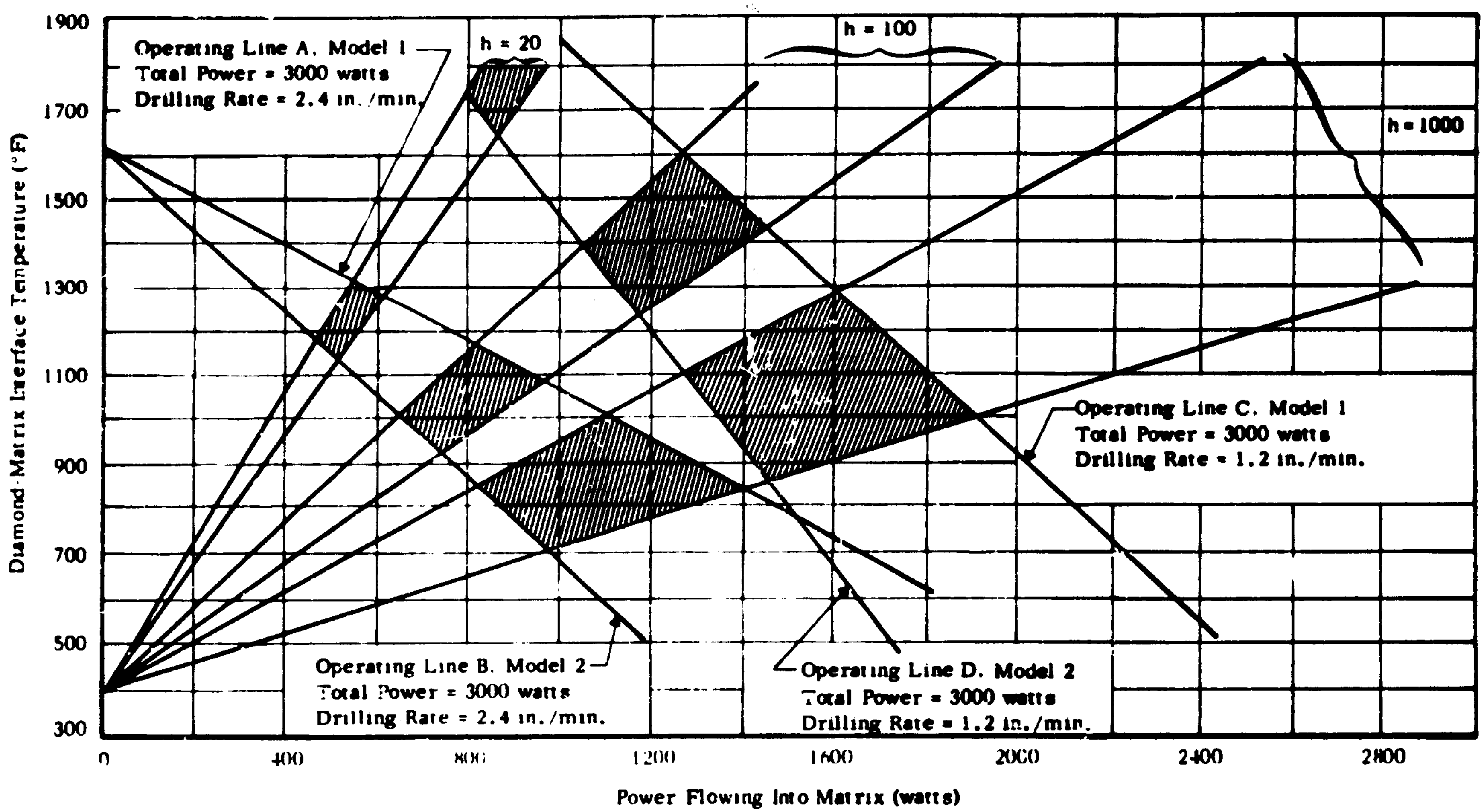


FIGURE 21 OPERATING LINES FOR DRILL SYSTEM

where T_{av} is in ^{o}C and W_1 is in watts, or:

$$T_{av}' = 0.553\ (3000-W_1) \qquad \text{(C-3)}$$

where T_{av}' is in ^{o}F.

Here we have assumed that 3000 watts total power is required to drill at 2.4 in/min. Since T_{av}' is the average temperature of the chips (above the ambient temperature), the chip temperature T_c is $T_{av}' - 40^{o}F$. If we assume that the chip temperature is the same as the diamond-matrix interface temperature, we may also show on Figure 21 an operating line for the matrix-diamond interface. This line is labelled "A" and has a negative slope as seen in Equation C-3. For Model 2, we have found that

$$T_c - T_1 = 0.39\ W_1$$

Therefore, the matrix-diamond interface temperature T_1 is

$$T_1 = T_c - 0.39\ W_1 = T_{av}' - 40 - 0.39\ W_1$$

$$= 0.553\ (3000 - W_1) - 0.39 W_1 - 40$$

$$= 1620 - .943\ W_1$$

This operating line is designated line B on Figure 21.

Summarizing these conditions, if 3000 watts total power is required to drill at a rate of 2.4 in/min, the diamond-matrix interface temperature is given by the following equations for the complete mixing model or the "stagnant chip boundary layer model."

Model 1 $T_1 = 1620 - .553\ W_1$ (Line A)

Model 2 $T_1 = 1620 - .943\ W_1$ (Line B)

The zone between these operating lines is a steady-state operating region for the drill system. Other operating lines can be drawn depending upon the total power required and the actual drilling rate. Thus, for example, if it is found that a drilling rate of only 1.2 in/min is possible with 3000 watts total input to the drill face, we obtain two new operating lines for these models as:

$$\text{Model 1} \quad T_1 = 2790 - .942\ W_1 \quad \text{(Line C)}$$

$$\text{Model 2} \quad T_1 = 2790 - 1.332\ W_1 \quad \text{(Line D)}$$

The operating lines for these drilling rates are also shown in Figure 21 and the intersections of these lines with those giving the characteristics of the matrix-diamond interface based upon heat flow into the matrix may be obtained. Thus, the shaded zones in Figure 21 indicate potential operating conditions for the models and operating characteristics chosen. For example, if a total power of 3000 watts provided a drilling rate of 2.4 in/min, and a heat transfer coefficient of 20 Btu/hr-ft^2 ^{o}F, an operating temperature of the diamonds may be in the range of 1100 to 1300^{o}F, depending on the conditions at the interface of the bit and the chips. When between 400 and 600 watts will be supplied to the cooling water through the matrix, the chips will carry away 2400 to 2600 watts. If the same power (3000 watts) is required at the lower drilling rate of 1.2 in/min, the temperatures of the diamond-matrix interface will be above 1700^{o}F in a range where the diamonds may not be satisfactory.

It must be re-emphasized that the operating zones shown in Figure 21 do not take into account the heat flow from the chips to the drill wall along the flutes. A detailed examination of the effects of drill shaft heating by the chips requires a three dimensional heat transfer analysis of the drill system near the cutting zone with complete specification of the heat transfer and boiling taking place in the water filled annulus. This analysis is beyond the scope of our present program. However, some estimates of the effects of chip heating can be made. For example, if we assume that radiation is the principal mechanism of heat transfer from the chips to the drill shaft, the rate of cooling of chips for the spiral mode of motion was given in Figure 16. The maximum heating occurs in the first few inches of travel of the chips along the drill shaft. In Section V-B it was shown that the heat from the matrix material was transferred into the cooling water within several inches of the drill face. By superposition of the upward heat flow along the drill shaft with the radial heat flow into the shaft, we may estimate the increase in the drill shaft temperature (and equivalently in the diamond matrix interface temperature) in the zone behind the drill face.

From Figure 16, at a drilling rate of 1.2 inches per minute, the temperature of the chips decreases from about 1710°K to 1140°K in the first 10 inches of travel along the shaft. The heat lost by the chips is approximately 860 watts; if half of the heat lost is transferred to the rock and half to the drill shaft, 430 watts flow into the drill shaft in this zone. The temperature difference between the drill shaft and the cooling water required to transfer this amount of heat is given below for several values of the heat transfer coefficient:

h (Btu/hr ft^2 °F)	ΔT (°F)
10	620
20	310
50	125
100	60
200	30

For reasonably high values of the heat transfer coefficient, the temperature rise of the drill shaft caused by chip heating is small compared to the rise in temperature of the matrix-diamond interface temperature for an equivalent upward flow of heat. This is a result of the large heat transfer area of the drill shaft surface compared to the small cross sectional area of the drill shaft through which heat from the matrix must flow. For higher drilling rates, e.g., 2.4 in/min, the effects of the chip heating will be smaller because the initial chip temperature is considerably lower and the radiation heat transfer from the chips to the shaft would also be lower. The decrease in radiation heat transfer is offset by the larger view factor of the drill shaft by the chips; however, the fourth power dependence of the radiation heat transfer on temperature should more than compensate for the larger view factor.

In the slug flow mode of chip transfer, heating of the drill shaft by the chips will be significantly larger, so that higher shaft temperatures would result. Experimental measurements will have to be carried out on an operating system to establish the mode of chip transfer and evaluate drill shaft temperatures near the cutting zone. Drill burnout may be a problem if slug flow is predominant and high convection coefficients are not achieved near the drill face.

The effects of chip heating of the drill shaft are to increase the level of the operating lines given in Figure 21. The increase is inversely proportional to the convection coefficient. Furthermore, the slopes of the operating lines also change, because as more heat is withdrawn from the drill face into the cooling water, the initial chip temperature is decreased and the heating of the drill shaft by the chips decreases. These factors have the effect of moving the intersection zones shown in Figure 21 slightly upward, depending upon the drilling rate and the convection coefficient. The over-all effect should not be large provided the spiral mode of chip motion predominates.

The maximum effect of any stoppage of cooling water on the diamond-matrix interface temperature can be inferred from the intersection of operating lines A and B or C and D with the ordinate for zero power flowing into the matrix.

VI. FACTORS AFFECTING DRILL PERFORMANCE

A. EFFECT OF OUTGASSING FROM ROCKS

Low pressure gas conductances for flow from the hole bottom upward past the drill were calculated for both molecular and viscous flow regimes. The primary objective was to determine the gas pressure resulting from outgassing of the volatile constituents of the rock at the drilling zone. High gas pressures may significantly affect the effective thermal conductivity of the chips and lead to higher heat transfer rates from the chips to the drill and surrounding rock.

The combined gas conductances of the annuli between the drill and the hole and between the inner and outer tubes were 4.145×10^{-2} liters/sec for molecular flow and 55.1×10^{-2} liters/sec for viscous flow (Dushman, 19[illegible]).

The product aP_{μ} is the controlling criterion for viscous or molecular flow. Here "a" is the characteristic cross-sectional dimension, in centimeters, of the flow passage and P_{μ} is pressure in microns. The division between flow regimes can be stated:

When $aP_{\mu} > 500$, the flow is viscous.

When $aP_{\mu} < 5$, the flow is molecular.

When $5 < aP_{\mu} < 500$, the flow is in the transition range.

Based on the outer annulus width, $a = .127$ cm, 39.4×10^{-3} torr is the maximum pressure for molecular flow and 3.94 torr is the minimum for fully-established viscous flow. Between these pressures is a transition region with mixed flow effects.

We calculated the maximum gas release rate for molecular flow and the minimum gas release rate for viscous flow with the following assumptions:

1. Lunar atmospheric pressure is 10^{-10} torr.
2. Molecular weight of 16 is typical for probable gases encountered (oxygen, nitrogen, water vapor).
3. Drilling rate is 2.4 inches per minute.
4. Density of lunar rock is 2.7 gram/cm^3.

Based on these assumptions, molecular flow will exist if the released gas is less than 0.36 ppm by weight of the rock. If the gas release exceeds 241 ppm or 0.024% by weight of rock, viscous flow will be fully established near the drill. These calculations suggest that gas pressure of the order of 1-10 torr may be present in the chips if volatiles are present in the rock. In this pressure range, the conductivity of a powder is increased significantly over that in vacuum.

Experimental data on vapor generation during rock drilling (and heating) and the effects of the vapor on heat transfer in a hot chip system are required before the effect of rock outgassing on drill performance can be fully evaluated.

B. CHEMICAL REACTIONS OF THE DRILL SYSTEM

The diamond drill consisting of diamonds imbedded in a tungsten carbide with Co (or Ni) or TiC-Co (or Ni) additives is not expected to react to any significant extent with either the lunar rock or the cooling water of the drill, if there should be a leak.

To estimate the reactivity of these materials, we have assumed the maximum operating temperature of the drill to be 1000°C. At this temperature, the silicate minerals, which are assumed to compose most of the lunar rock, are extremely stable with respect to carbon reduction. A single typical calculation will suffice to demonstrate the stability. The reaction of carbon (or diamond) with sodium silicate:

$$C(c) + Na_2\,SiO_3 \rightarrow SiO_2\,(c) + 2\,Ni\,(c) + CO\,(g) \qquad (1)$$

has a free energy at 1000°C of + 51.4 k cal/mole. This means that the maximum rate of release of carbon monoxide during drilling would be less than 1.5×10^{-8} g/cm^2-sec. This rate of release would correspond to a maximum diamond recession rate of 1.83×10^{-8}.cm/sec or about 0.5 mil over a 20 hour period of drilling.

If the drill should encounter water vapor in drilling the lunar rock or if some of the cooling water accidentally comes in contact with the diamond drilling elements, chemical reactions would be possible. Binford and Erying (1956) studied the steam carbon reaction:

$$C\,(\,s\,) + H_2O\,(g) \rightarrow CO\,(g) + H_2\,(g) \qquad (2)$$

at temperatures of 900 - 1300°C and steam pressures of 1 - 40 μ at 1000°C, the measured rate of reaction of carbon was 0.25×10^{-7} moles/cm^2 min, independent of pressure between 5 and 40 μ. If diamond reacts at the same rate as graphite (an assumption that we shall examine further below). then the rate of recession of the diamond drill elements at 1000°C in the presence of water vapor would be of the order of 3.4×10^{-5} mils/min or 0.04 mils over a 20 hour period.

There have been very few experimental reaction rate studies on diamonds. For purposes of estimation, it seems reasonable to assume that the upper limit of the rate of reaction of diamond will be given by the rate of reaction of graphite under similar conditions. One reaction that has been studied directly on diamond is oxidation. Evans and Phaal (1962) measured the rate of oxidation of diamond at temperatures of a range 650 - 1350°C and oxygen pressure of 0.2 torr to one atmosphere. They found evidence for oxygen catalyzed graphitization and showed that the rate of oxidation of diamond is controlled by the rate of oxidation or the carbon layer which forms on the surface.

The carbide-metal composite matrix is also expected to be unreactive under the anticipated temperature conditions. Any loosening of the diamond in the matrix is more likely to have a mechanical than a chemical cause.

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APPENDIX A

THE TEMPERATURE DISTRIBUTION OF AN INFINITE STRIP SOURCE IN A MOVING MEDIUM

Consider an infinite strip heat source of uniform intensity (q units of heat per unit length per unit time) and of width 2d, located at the z = o plane as shown in Figure A-1. The surrounding medium, infinite in extent, has a density ρ, a specific heat c, and a thermal conductivity k, and it is moving with a uniform velocity U in the negative z direction. Then it can be shown* that the temperature rise of the medium over ambient temperature is given by:

$$T\,(x',\, z') = \frac{q}{\pi\rho cU}\, e^{-z'} \int_{-\alpha}^{\alpha} K_o \left\{\left[z'^2 + (x'-\xi')^2\right]^{1/2}\right\} d\xi'$$

where x' and z' are normalized coordinates given by:

$$x' = \frac{\rho cUx}{2k}, \quad z' = \frac{\rho cUz}{2k},$$

α is a dimensionless parameter given by:

$$\alpha = \frac{d\rho cU}{2k},$$

and K_o is the Hankel function of order zero.

This expression shows that the temperature decreases exponentially for positive values of z', i.e., that we have an exponential boundary layer in the positive z direction of thickness $2k/\rho cU$. Furthermore, for

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*This integral can be formed from the formula of the line heat source given by H. S. Carslaw and J. C. Jaeger, "Conduction of Heat in Solids", Oxford University Press, 1950, page 224.

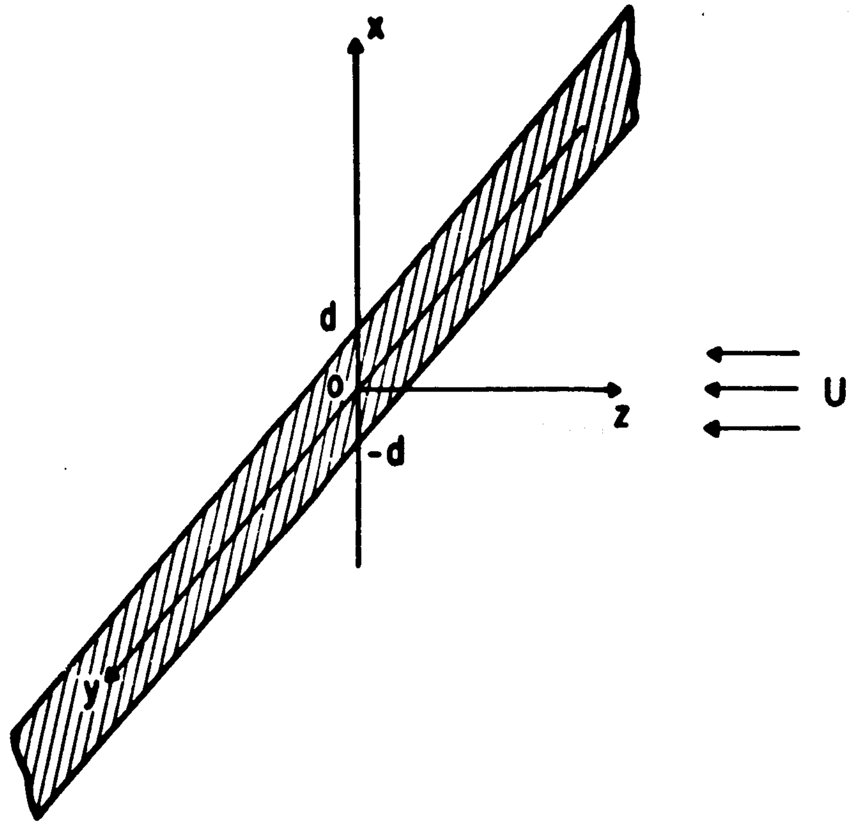

FIGURE A-1 INFINITE STRIP SOURCE IN MOVING MEDIUM

z' small and x' large, the asymptotic expansion of K_o shows that there is an exponential boundary layer in the x' direction (positive or negative) of the same thickness ($2k/\rho cU$). The existence of these steep boundary layers means that, if $\rho cdU/k$ is 1 or larger, only the part of the medium which is within a distance 2d from the centerline of the source is influenced by the source for $z > o$; in other words, the medium outside this region is essentially at ambient temperature. It also means that each element of the source of length of the order of 2d influences heavily only the part of the medium which is near it. The implication of this last statement is that, for a strip heat source which is bent in the xy plane, the temperature rise in the medium within a distance 2d from the centerline of the source can be estimated accurately from the formula of the straight strip source as long as the curvature of the bent source is large as compared to d.

The temperature rise at $z' = o$ is given by:

$$T(x') = \frac{q}{\pi \rho c U} \int_{-\alpha}^{\alpha} K_o(|x' - \xi'|)\, d\xi'$$

If

$$I(t) = \frac{2}{\pi} \int_{o}^{t} K_o(t')\, dt'$$

it can be shown by a simple transformation of variables that:

$$T(x') = \frac{q}{2\rho c U} [I(\alpha + x') \cdot I(\alpha - x')]$$

Whereas K_o is a tabulated function, I(t) is not. We have computed I(t) by numerical integration using the trapezcidal rule and the values of K_o given in Jahnke and Emde's "Tables of Functions". The results are shown in Figure A-2. The accuracy is better than 5%.

With the curve of Figure A-2, the temperature rise on the plane of the source can be computed for all values of x'.

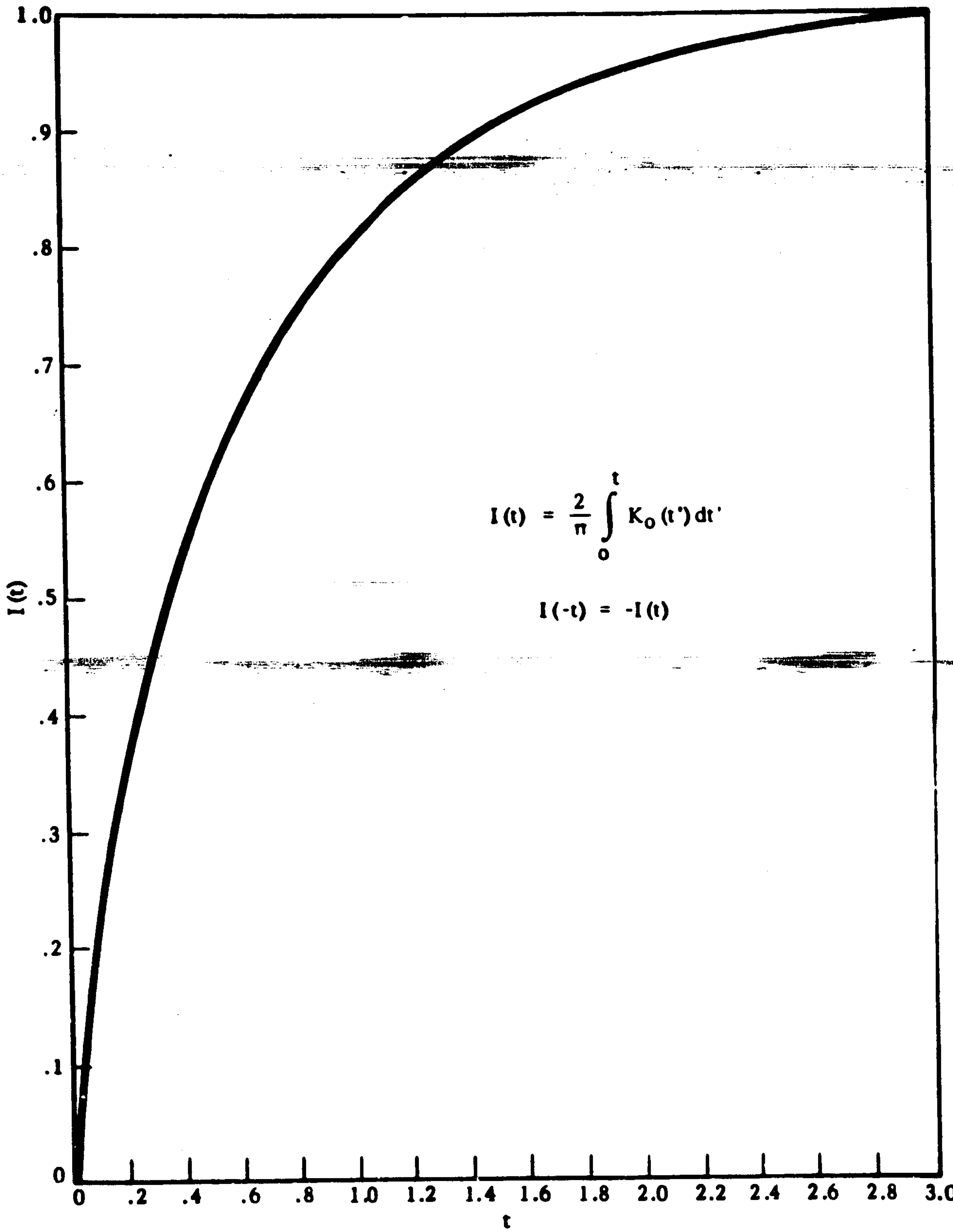

FIGURE A-2 THE INTEGRAL OF THE HANKEL FUNCTION OF ORDER ZERO

APPENDIX B

REFERENCES FOR DATA GIVEN IN FIGURES OF SECTION IV

The following list of references can be used to obtain more detailed information on the data presented in Section VI.

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APPENDIX D

THERMAL CONTROL SUBSYSTEM DESIGN

The Westinghouse concept of the lunar drill requires a thermal control system for the drill bit to prevent the destruction of the bit and to conserve the integrity of the core sample.[1] The thermal control concept is based on a closed cycle 2-phase system[2] utilizing the latent heat of vaporization of water.

The analyses that led to the sizing and configuration of the system are as follows:

D.1 LINE SIZING OF COOLING SYSTEM

The first studies were made to determine the minimum line sizes required using water vaporization cooling to remove 3 kW of heat from the bit. Line sizes have been determined for a number of possible operating conditions using a gravity flow system only.

The basic equations used to determine the line sizes are:

1. $Q = \pi D^2 V/4 = 0.785\ D^2 V\ ft^3/sec$

   Q = quantity of flow (ft^3/sec)

   D = inside diameter of pipe (ft)

   V = fluid velocity in pipe (ft/sec)

2. Reynolds No., $N_{RE} = dVD/v$

   d = fluid density (lb/ft^3)

   V = fluid velocity in pipe (ft/sec)

   D = inside diameter of pipe (ft)

   v = fluid viscosity (lb/ft-sec)

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1. pp. 3-149 of Westinghouse proposal "Development of a Lunar Drill System."

2. pp. 3-150 and p. B-29 of Westinghouse proposal "Development of a Lunar Drill System."

3. **Head loss, $h = fl\,V^2/2\,g\,D$**

h = friction loss in pipe (ft of fluid)

l = length of pipe (ft)

V = fluid velocity in pipe (ft/sec)

D = inside diameter of pipe

g = gravity constant (32.17 ft/sec^2)

f = friction factor - determined from Moody graph of factors for flow in pipe versus Reynolds numbers.

Minimum line sizes for a particular operating condition were determined as follows:

a. Flow rates (Q in ft^3/sec) were determined for a particular boiling temperature at the drill bit.

b. Using this flow rate in equation (1) values of fluid velocity (V) were determined for numerous line diameters (D).

c. Reynolds numbers were determined from equation (2) for specific values of fluid velocity and pipe diameter.

d. Friction factors were selected from the Moody graph for each specific value of Reynolds number.

e. The head loss in the pipe was determined from equation (3) assuming a fixed value for pipe length (l). Values of fluid head loss determined for the steam line were converted to liquid water head loss values.

f. Values of head loss versus pipe diameter for both the water line and the steam line were then plotted using 16.5 feet of head loss as a maximum. This figure was used as a maximum because it corresponds to 100 feet of liquid head on the moon.

By using the resulting two curves of liquid head loss versus pipe diameter and with a maximum available liquid head of 16.5 feet, the minimum total cross-sectional area of both the water and steam lines can be determined.

Results of the above calculations for systems with specified operating conditions are tabulated on the following page.

COOLING SYSTEM CIRCUIT

	1 ONE LINE	2 ONE LINE	3 TWO LINES	4 ONE LINE	5 THREE LINES
Boiling Temperature, °F	197	392	392	158	392
Boiling Pressure, PSIA	10.8	225	225	4.5	225
Condensing Temp., °F	158	390	390	150	390
Condensing Press, PSIA	4.5	220	220	3.7	220
Water line equivalent length, ft.	300	300	300	300	125*
Steam Line equivalent length, ft.	300	300	300	300	125*
Water line I.D. (in.)	0.175	0.153	0.109	0.104	0.082
Steam line I.D. (in.)	0.479	0.279	0.218	0.574	0.154

* 125 feet of equivalent length were used in this case after it was determined that shutoff valves in the drill rod sections could be eliminated. This is explained later in this report.

As a result of the first efforts in determining minimum line sizing, it became evident that a system operating nominally at 390°F would result in a system of less weight than one operating at a lower temperature. The line sizes would be smaller and contain less water. The thermal radiator (condenser) would be smaller and considerably lighter since it would be operating at a higher temperature.

At this point, it was decided to look at a three parallel line, high temperature (390°F) system, without shutoff valves in the drill rod sections to see if a weight savings might be realized. This meant that water in the lines would be lost when adding drill rod sections. Since the weight of valves was estimated at 5 pounds, the water lost in this type of operation could not exceed 5 pounds.

Elimination of the valves permitted calculations for line sizing to be done using 125 feet of equivalent length for the lines instead of 300 feet equivalent length. The resulting head loss versus pipe diameter curves are shown in figure D-1.

By using these curves and dividing the 16.5 feet of available head between both the water lines and the steam lines, any number of pipe diameter combinations may be used as long as their total head loss does not exceed the 16.5 feet. A minimum total pipe cross-sectional area is reached, however, when the water lines are 0.082 inches ID and the steam lines are 0.154 inches ID. In order to have a reasonable safety factor, it has been decided to use water lines of about 0.100 inches ID and steam lines of about 0.200 inches ID. From the curves, it can be seen that the piping head losses then become:

• Water lines head loss	1.2 ft
• Steam lines head loss	3.9 ft
• Total head loss	5.1 ft

With 16.5 feet of head available, these line sizes become more than adequate to ensure sufficient flow in a gravity feed system.

D.2 SYSTEM OPERATION

Operation of the cooling system is explained now with reference to figure D-2.

At the start of the drilling operation, the condenser portion of the system is pressurized and separated from the drill rods and bit. These sections are open to the vacuum atmosphere. Valves A, B, C, and D are closed.

a. Drill rod and bit section are connected to condenser portion for start of drilling operation. Valve D is closed.

b. Valve A is opened charging water into drill rod and bit section.

c. Valve C is opened and the system is ready for drilling operations.

d. When new section of drill rod is required, valve A is closed, valve B is opened and drilling continues with valves B and C open until water in the

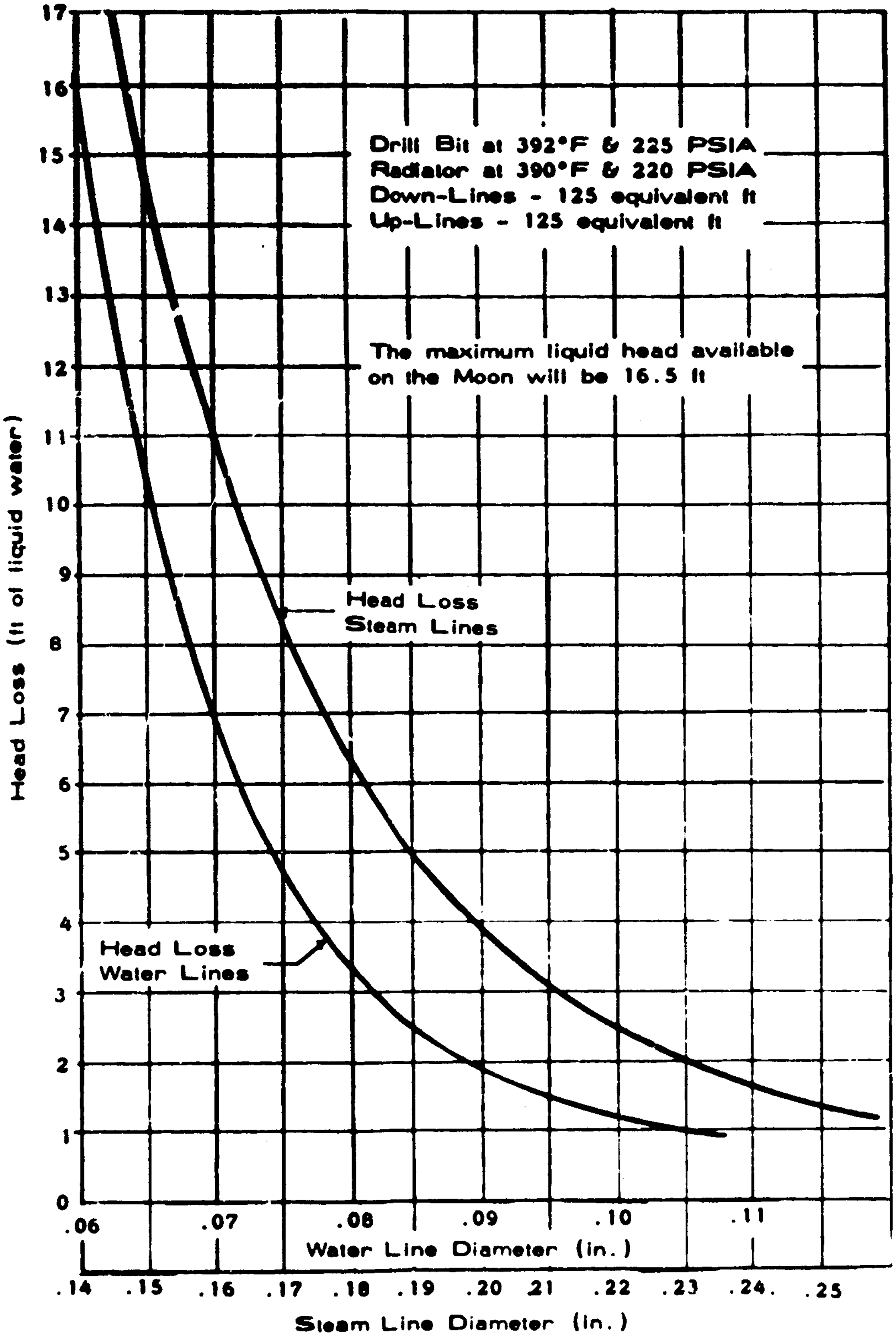

Figure D-1. Head Loss vs Line Diameter Drill Bit Cooling - 3 kW

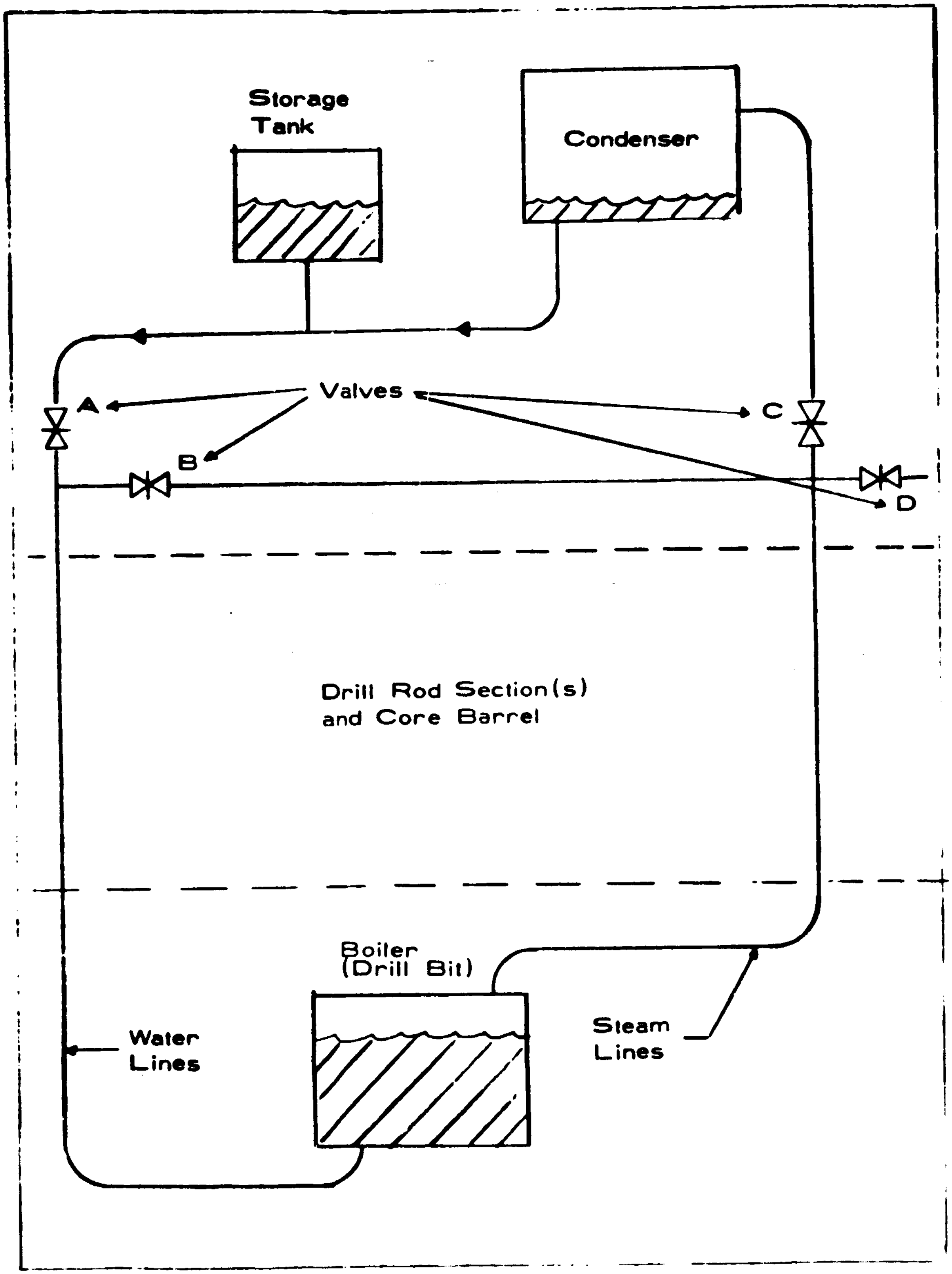

Figure D-2. Drill Cooling System Schematic drill bit section of the system is evaporated. It will collect in the condenser section of the system.

c. All three valves will then be closed and drill bit section is vented to vacuum by opening valve D. The system is then separated to add a new section of drill rod. Water vapor left in the drill rod and bit section will be lost to the vacuum atmosphere.

f. The above procedure will be repeated as necessary to reach the desired drill depth of 100 feet.

If the water and steam line diameters are respectively 0.100 inch and 0.200 inch and drill rod sections are 5 feet long, the total amount of water lost to the vacuum atmosphere when drilling to a depth of 100 feet will be approximately 0.67 pound. This figure includes both the weight of steam in all of the vertical lines and the weight of water that might remain in the drill bit.

D.3 BOILING SURFACE AREA REQUIRED

Some explanation of the physical laws of heat transfer through boiling water must be made in order to justify the amount of heat transfer surface required. Figure D-3 shows the characteristics of a heat transfer capability of a heated surface in contact with water at atmospheric pressure.

Zone A, to 15°F - This is the so-called convection cooling zone. Boiling takes place in the heated water at some point away from the surface.

Zone B, from 15°F to 45°F - This is the nucleate boiling zone where individual bubbles of vapor are formed at the hot surface, break away and travel upward through the water to the atmosphere.

Zone C, from 45°F to approximately 440°F - This is a transition zone where increasing the temperature of the heated surface actually reduces the amount of heat transferred. In this area, the vapor partially insulates the heated surface from the water until about 440°F is reached on the hot surface. At this point the surface becomes completely covered with a sheath of vapor and all heat transfer is through this vapor barrier.

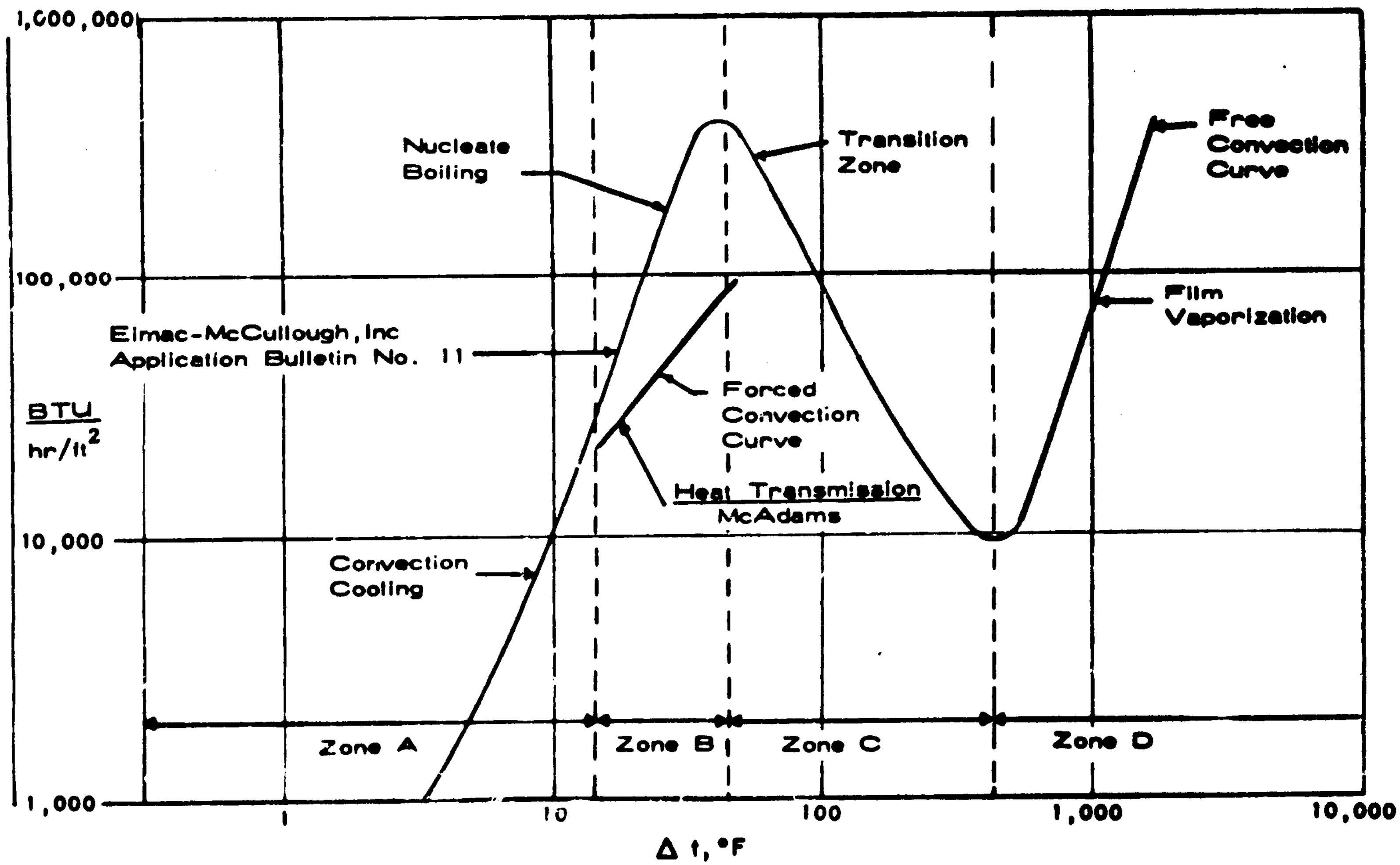

Figure D-3. Heat Transfer From Hot Surface to Boiling Water at 1 ATM

Zone D, of 440°F and above - This is the film vaporization and heat transfer increased until at about 18°F the previous maximum heat transfer rate is again reached.

In cooling of the drill bit, temperature of the diamonds cannot be permitted to exceed 800°C (1472°F); therefore, heat transfer by boiling must be accomplished below the critical temperature difference of 45°F. The amount of heated surface required in the drill bit must be selected based on the forced convection curve in figure D-3 rather than the free convection curve. The practical limit of heat flux from this curve indicates a maximum of 100,000 Btu/hr ft^2 and for this system a limit of 85,000 Btu/hr ft^2 was used. For a 3-kW heat dissipation, approximately 17.5 square inches of boiling surface area would be required. Proportionally less surface would be required for lesser heat dissipation.

D.4 PROBABLE COOLING LOAD

At the time of writing the proposal, it was assumed that all of the 5 kW of power available was used with 60-percent overall efficiency. This means 3 kW of heat must be dissipated at the drill bit when all other losses are neglected.

From curves of drill penetration rate, thrust, torque and rpm for granite as shown in the Westinghouse proposal, it appeared that 3 kW of heat dissipation in the drill bit might be unrealistic. For example, the amount of power being dissipated in a typical bit, drilling through granite at 1.2 inches min and 500 rpm with an axial thrust of 400 pounds, is about 425 watts. Based on this information, it appeared that a bit cooling system capable of dissipating 1 kW would be adequate. A breadboard thermal control system was designed and tested to determine the feasibility of a 1-kW cooling system. The testing was successful.

APPENDIX E
THERMAL CONTROL SYSTEM FEASIBILITY TEST

E.1 GENERAL

The purpose of the thermal control test was twofold; first, to show that the thermal control manifold concept could remove a specified minimum amount of heat, and secondly, that the coolant passages were sized so that a vapor lock condition could be avoided.

This test was conducted at the Westinghouse Aerospace Test Laboratory. A drawing of the drill bit blank used in this test is shown in figure E-1. The major modification of this blank from the previous blanks is the length. A photograph of the test setup is shown in figure E-2. The apparatus was enclosed in a plywood box filled with loose insulation to minimize heat losses to the room.

Heat was applied from an electrical resistance heater wrapped around the bit blank. Removal of heat from the system was accomplished through a water cooled condenser at which point the amount of heat removed was measured.

In the tests, it was necessary to apply 1,420 watts to the drill bit blank in order to measure over 1,000 watts being removed at the water cooled condenser at the steady state condition. Approximately 400 watts were dissipated from the test setup to ambient room air. Thermocouples were mounted on the outer surfaces of the insulated enclosure around the system and the bit blank. This allowed the calculation of heat lost through the insulation. Calculations are shown in paragraph E.2.2 of this appendix, with the resulting heat exchanged and system losses summarized in table E-1.

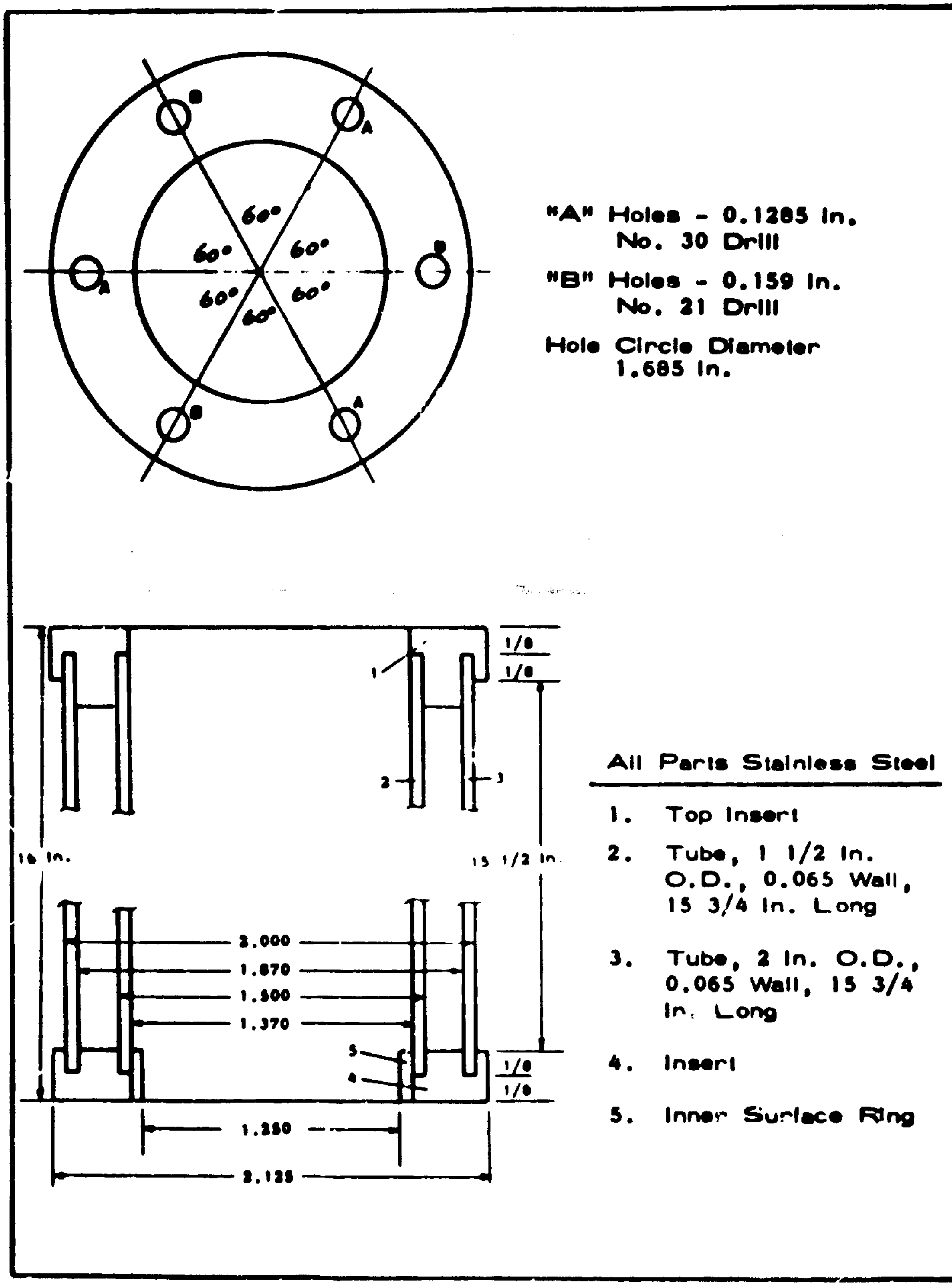

Figure E-1. Thermal Control Test Bit Without Matrix

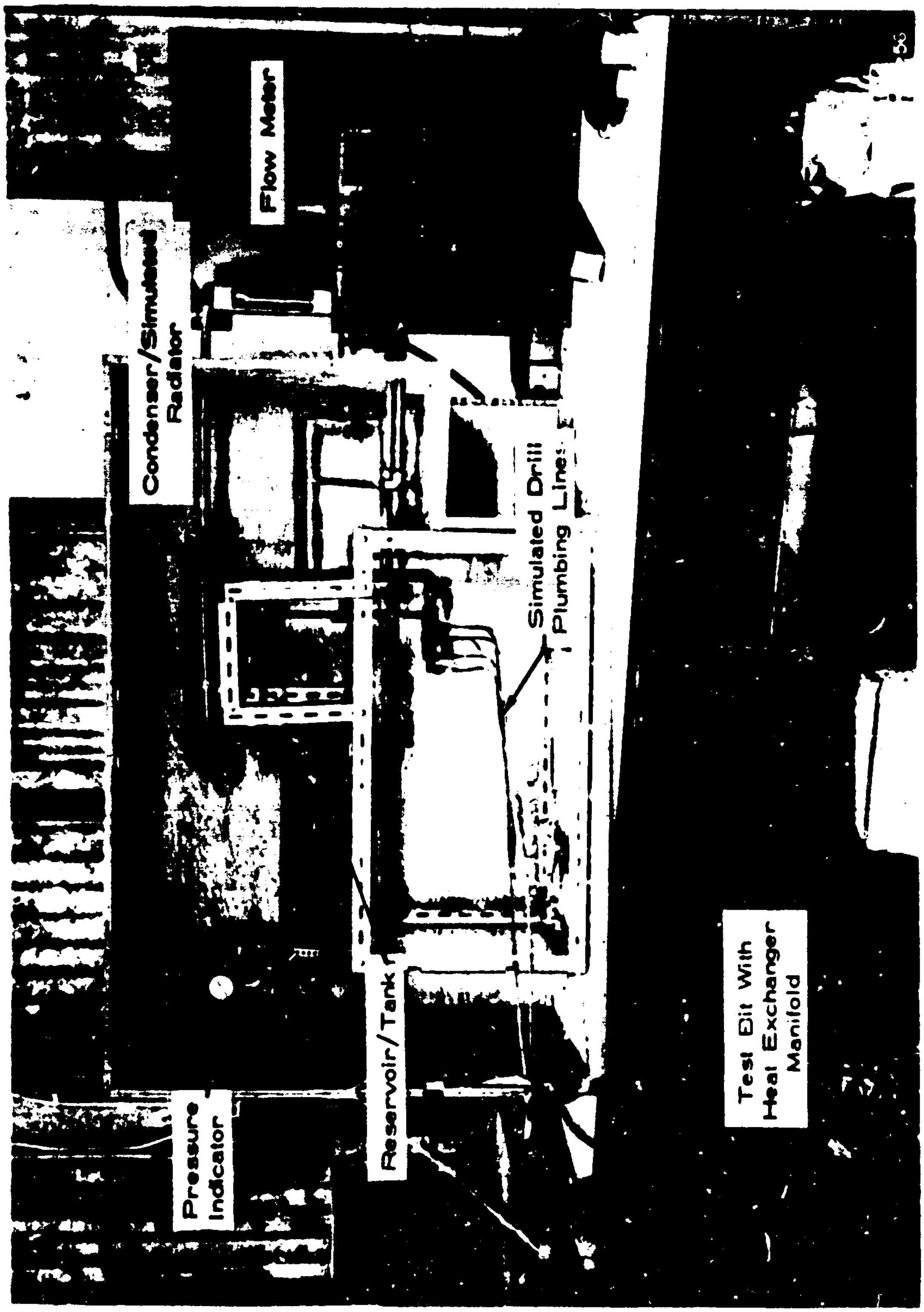

Figure E-2. Thermal Control Test Setup

TABLE E-1

THERMAL CONTROL TEST RESULTS

TC	LOCATION
1	Bottom surface of drill bit blank
2	Inner external surface of drill bit blank
3	Inner external surface of drill bit blank
4	External surface, 1 in. down from top, adjacent to water line.
5	External surface, 1 in. down from top, adjacent to steam line.
6	Water line, 1/8 in. O.D., entering drill bit blank
7	Steam line, 5/32 in. O.D., entering drill bit blank
8	Cooling water entering condenser
9	Cooling water leaving condenser
10	Side of insulated box (Middle)
11	Insulation exterior on drill bit blank
12	Top of insulated box (Middle)
13	Room Temperature

DATA FROM FIVE CONSECUTIVE READINGS — 30 Nov. 65

Reading	1		2		3		4		5	
Time	3:00		3:15		3:30		3:45		4:00	
Watts In	1420		1420		1420		1420		1420	
Flow, cc/min.	25.0		24.7		24.7		24.0		22.3 *	
Pressure, PSIG	43		46.5		52		56		63	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
TC 1	131	267.8	133	271.4	135.5	275.9	137	278.6	140	284
TC 2	135	271.4	137	278.6	139	282.2	141	285.8	143.5	290.3
TC 3	120	248	121.5	250.7	123.5	254.3	126	258.8	128	262.4
TC 4	162	323.6	163	325.4	166.5	331.7	168.5	335.3	172	341.6
TC 5	173	343.4	174	345.2	177	350.6	179	354.2	183	361.4
TC 6	146	294.8	148	298.4	149	300.2	152	305.6	152	305.6
TC 7	145	293	147.5	297.5	149	300.2	152	305.6	154	309.2
TC 8	46.5	115.7	48.5	119.3	40.5	104.9	41.5	106.7	41.5	106.7
TC 9	140	284	143	289.4	145.5	293.9	148	298.4	150.5	302.9
TC 10	28	82.4	28	82.4	28	82.4	28.5	83.3	28.5	83.3
TC 11	107	224.6	108.5	227.3	110	230	111	231.8	112	233.6
TC 12	29	84.2	29	84.2	29.5	85.1	29.5	85.1	30	86.0
TC 13	23	73.4	24	75.2	24	75.2	24.5	75.2	24.5	75.2
Watts out	1062		1048		1066		1037		963 *	
Bit Loss	208		210		214		216		218	
Box Top Loss	50		42		46		46		50	
Box Side Loss	168		134		134		151		151	
Box Base Loss	21		21		21		21		21	
TOTAL	1509		1455		1481		1471		1403	

The test system was initially designed to remove 1 kW from the bit blank when operating at a maximum pressure of 210 psig and a maximum temperature of 390°F. To expedite the test, off-the-shelf hardware was used in construction. As a result, the lines and condenser were oversized and resulted in the removal of 1 kW with the system operating at 50 psig and 300°F. This difference in operating points does not effect the validity of the tests since the addition of 1 kilowatt into the bit did not cause superheating of the coolant.

A tabulation of the test results appears in table E-1 describing the heat dissipation as well as thermocouple location and recordings. The following sections show the calculation of heat dissipation.

E.2 THERMAL CONTROL TEST RESULTS

E.2.1 Calculation of Watts Output

$$\frac{(\text{cc/min} \times 0.00220\ \text{lb/cc})\ (\text{enthalpy change of water B/lb})}{0.0569\ \text{B/min watt}} = \text{watts}$$

Reading Number 1

(25.0) (0.00220) (1099.7)/0.0569 = 1062 watts

Reading Number 2

(24.7) (0.00220) (1098.7)/0.0569 = 1048 watts

Reading Number 3

(24.7) (0.00220) (1115.0)/0.0569 = 1066 watts

Reading Number 4

(24.0) (0.00220) (1115.3)/0.0569 = 1037 watts

Reading Number 5*

(22.3) (0.00220) (1117.4)/0.0569 = 963 watts

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* On reading number 5, the line pressure on cooling water entering the condenser was fluctuating. The flow meter was indicating a lesser flow although no adjustment had been made. The lower wattage output calculated was due to thermal inertia that prevented the cooling water temperatures to adjust fast enough.

E. 2. 2 Calculation of Bit Insulation Loss in Watts

Q = (hc + hr) A Δt

watts = Q/3.415 B/Hr watt

hc + hr = heat transfer coefficient

A = surface area

Δt = temperature difference

A = (5 π) (18)/144 = 1.96 ft^2

hc + hr = 2.40 B/hr ft^2 °F for 150°F Δt (Marks pg. 377)

Reading Number 1

watts = (2.40) (1.96)(151)/3.415 = 208 watts

Reading Number 2

watts = (2.40) (1.96)(152)/3.415 = 210 watts

Reading Number 3

watts = (2.40) (1.96)(155)/3.415 = 214 watts

Reading Number 4

watts = (2.40) (1.96)(156.6)/3.415 = 216 watts

Reading Number 5

watts = (2.40) (1.96)(158.4)/3.415 = 218 watts

The thermocouple on the bit insulation was taped on with masking tape and indicated about 225°F. This was probably high because of the tape. The insulation was never too hot to lay your hand on it. 200 watts loss therefore is probably somewhat high.

E. 2. 3 Calculation of Heat Loss From Top of Box

watts = U A Δt/3.415 B/Hr watt

watts = 4.63 Δt

U = 1.64 B/hr ft^2°F

A = (2.00) (4.81) = 9.62 ft^2

Reading Number 1

watts = (4.63) (10.8) = 50.0 watts

Reading Number 2

watts = (4.63) (9.0) = 41.7 watts

Reading Number 3

watts = (4.63) (9.9) = 45.8 watts

Reading Number 4

watts = (4.63) (9.9) = 45.8 watts

Reading Number 5

watts = (4.63) (10.8) = 50.0 watts

The thermocouple was located in the middle of the top of the box and would indicate a temperature higher than the average for the top. The above wattage loss figures are higher than the actual losses.

E.2.4 Calculation of Heat Loss From Sides of Box

watts = $U A \Delta t / 3.415$ B/Hr watt

watts = $18.6 \Delta t$

U = 1.47 B/hr ft^2 °F

A = 43.2 ft^2

Reading Number 1

watts = (18.6) (9.0) = 167.5 watts

Reading Number 2

watts = (18.6) (7.2) = 134 watts

Reading Number 3

watts = (18.6) (7.2) = 134 watts

Reading Number 4

watts = (18.6) (8.1) = 151 watts

Reading Number 5

watts = (18.6) (8.1) = 151 watts

The thermocouple was located in the middle of the side of the box and would indicate a temperature higher than the average for the sides. The above wattage loss figures are higher than the actual losses.

E.2.5 Calculation of Heat Losses From Bottom of Box

No temperature measurements made, however, the "U" factor for the bottom would be 1.09 B/hr ft^2 °F. Assume surface temperature 7°F above room temperature.

watts = $UA\Delta t$/3.415 B/hr watt

U = 1.09 B/hr ft^2 °F

A = 9.62 ft^2

Δt = 7°F

$\therefore$ watts = (1.09) (9.62) (7)/3.415 = 21.4 watts